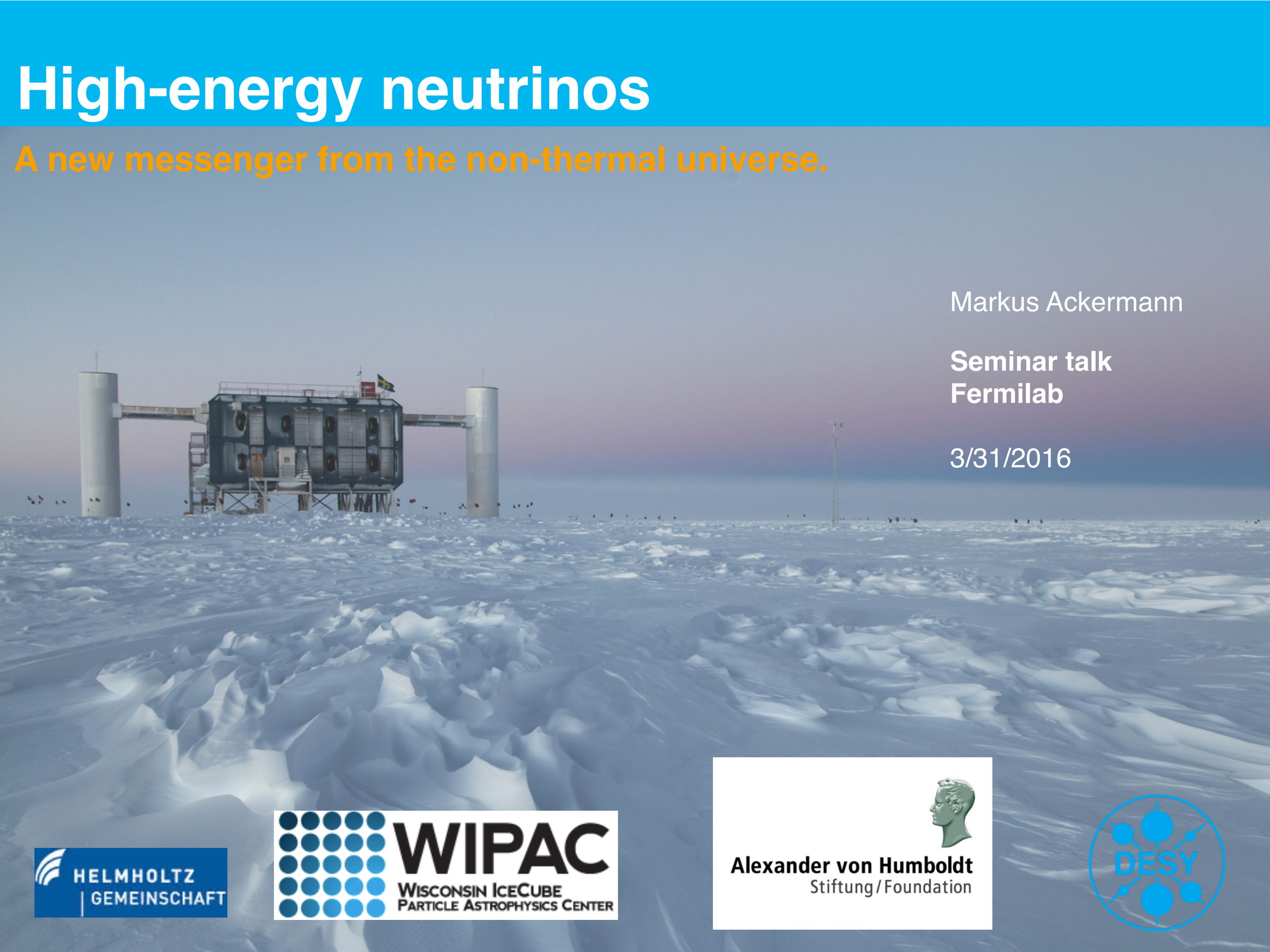
High-energy neutrinos

A new messenger from the non-thermal universe.



Markus Ackermann

Seminar talk
Fermilab

3/31/2016

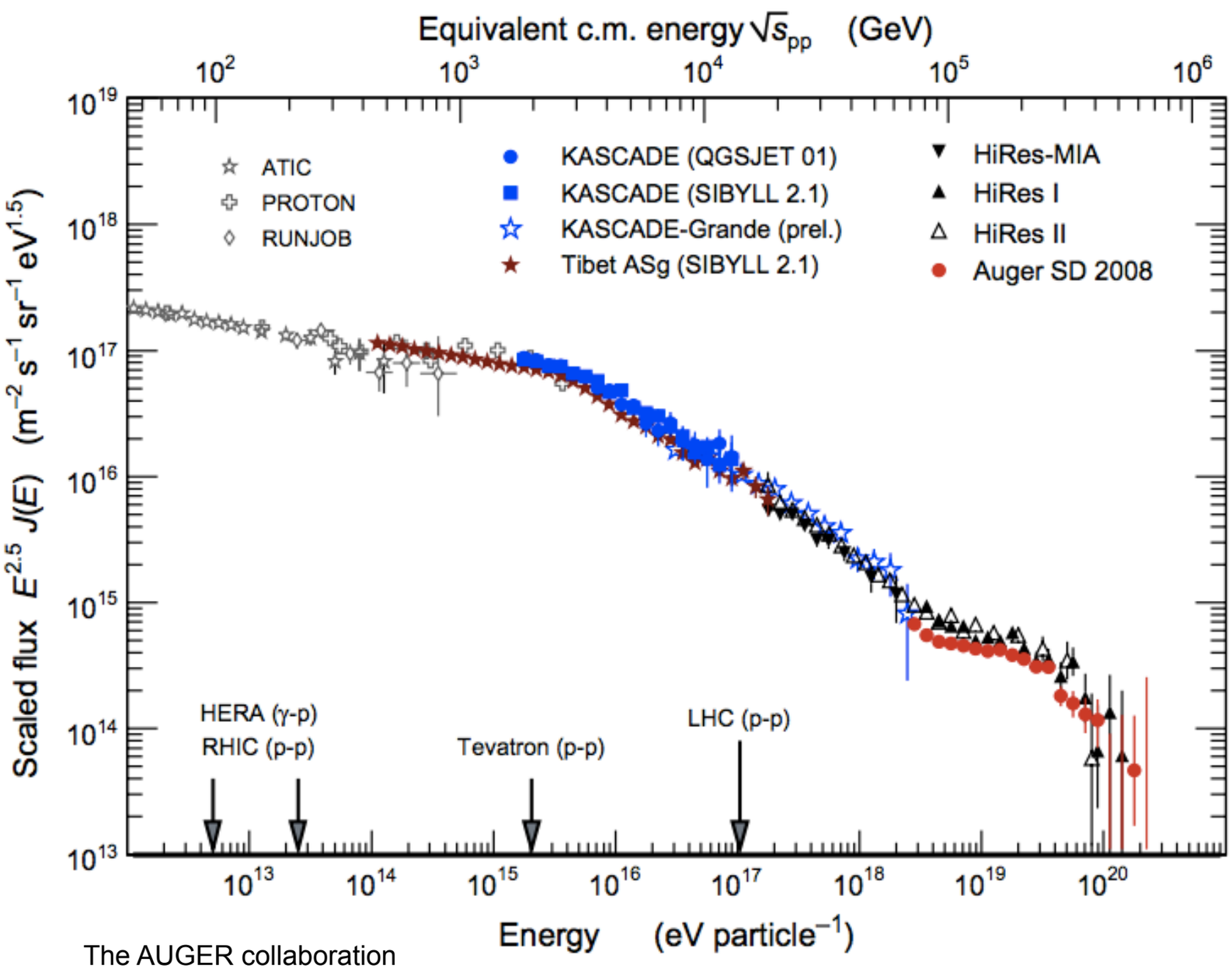
HELMHOLTZ GEMEINSCHAFT

WIPAC
Wisconsin IceCube Particle Astrophysics Center

Alexander von Humboldt
Stiftung/Foundation

DESY

High-energy astrophysics: The cosmic-ray puzzle.



The AUGER collaboration
New Journal of Physics 12 (2010) 035001

> **Cosmic rays** can be observed to energies **> 10^{20} eV**

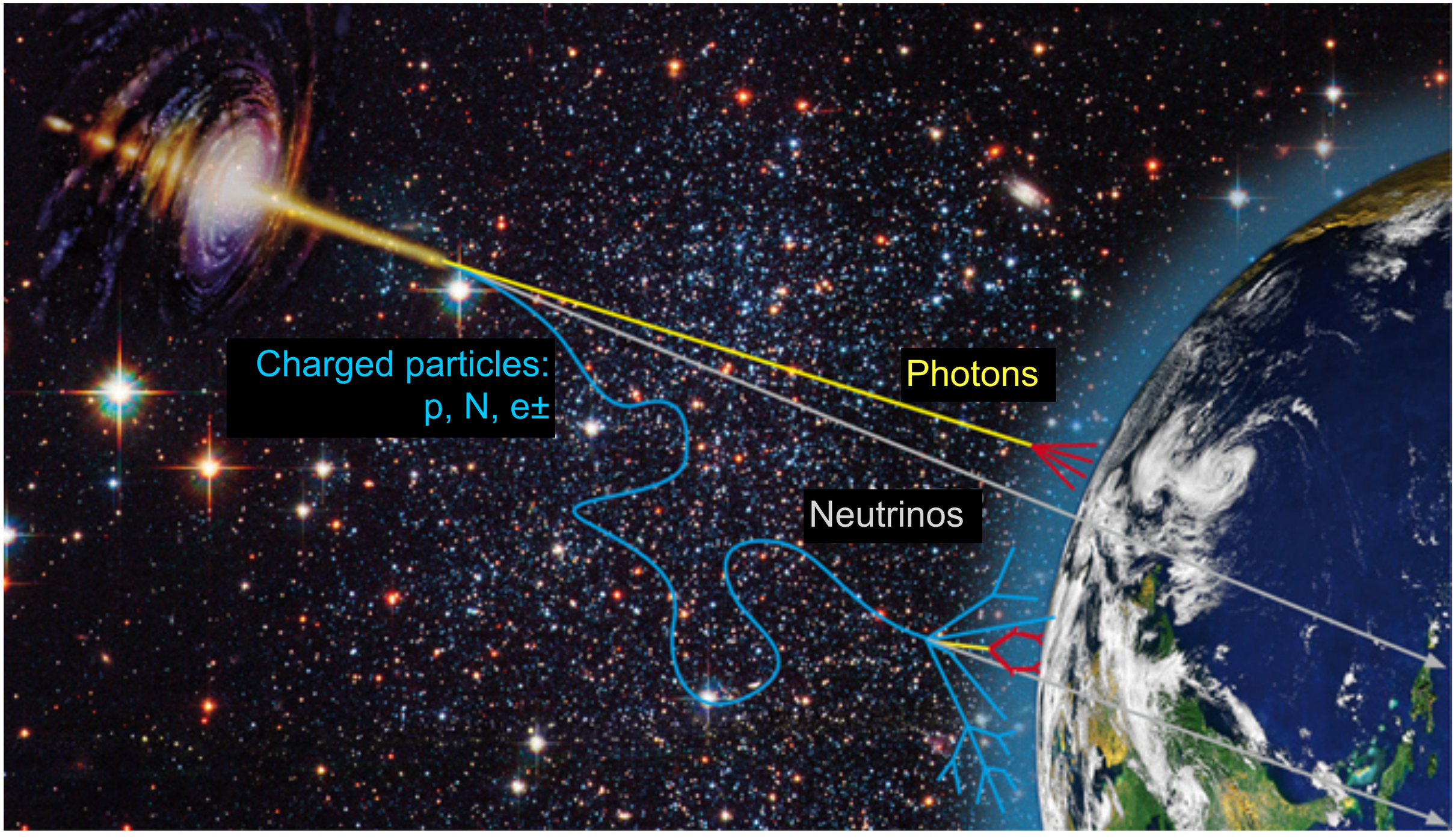
> Their **origin** is still **unknown,** even 104 years after their discovery.

> **Which sources** can accelerate particles to such high energies ?

> And what are the **physics processes** behind ?

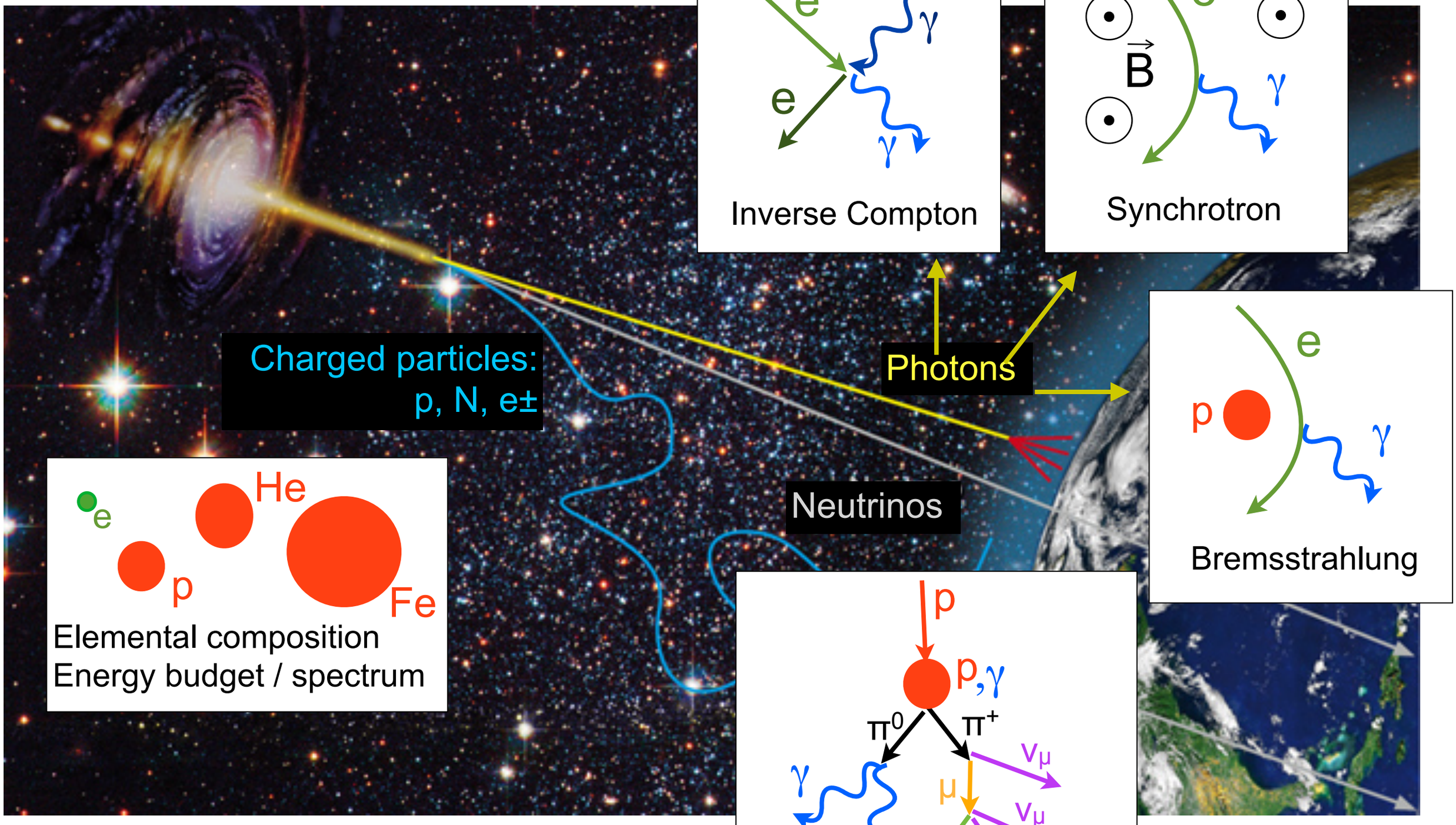
The cosmic-ray puzzle.

> Three messengers are available to study the non-thermal universe.



The multi-messenger approach.

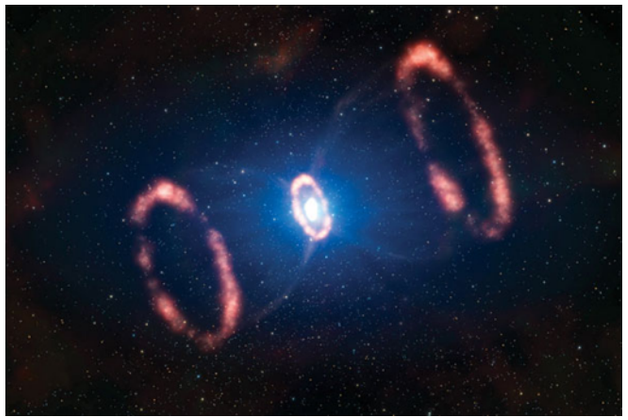
> Every messenger is unique.



> Neutrinos are a diagnostic of the **acceleration sites of protons and nuclei.**

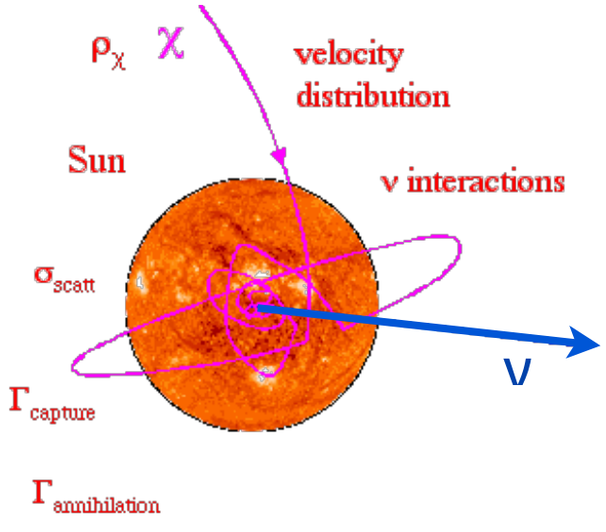
Neutrinos from dense environments.

Neutrinos can **escape dense environments:**



> High-energy neutrinos from core-collapse SNe.
(e.g. Ando & Beacom, 2005)

> Neutrinos from the cores of active galactic nuclei
(e.g. Stecker et al., 1991)

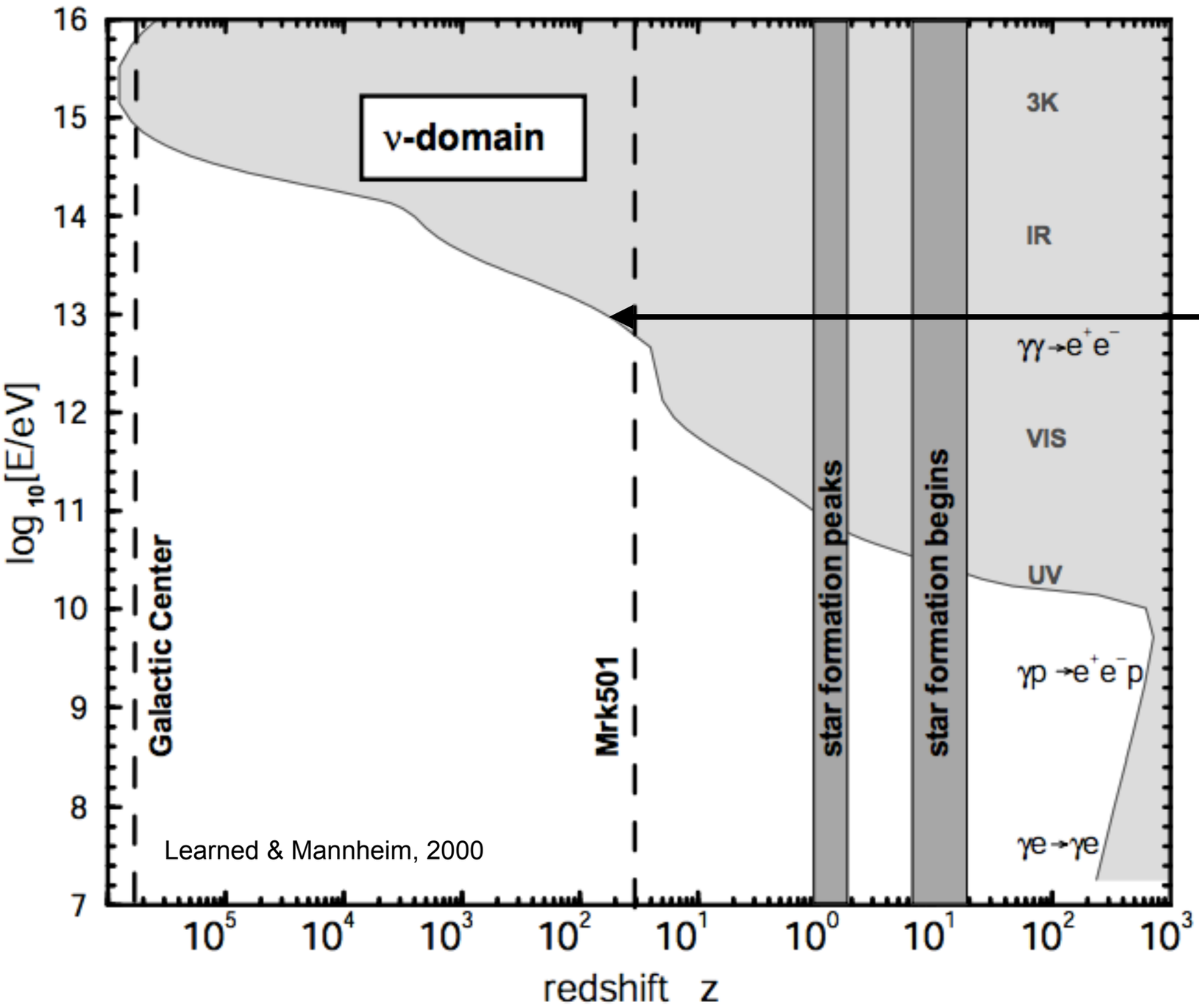


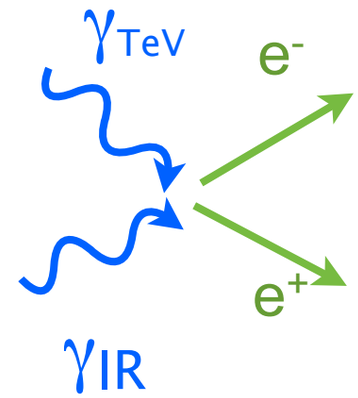
> High-energy neutrinos from dark matter annihilation in the sun.

The neutrino domain: PeV astronomy.

> Above 100 GeV the **universe** starts to turn **opaque for γ-rays**.

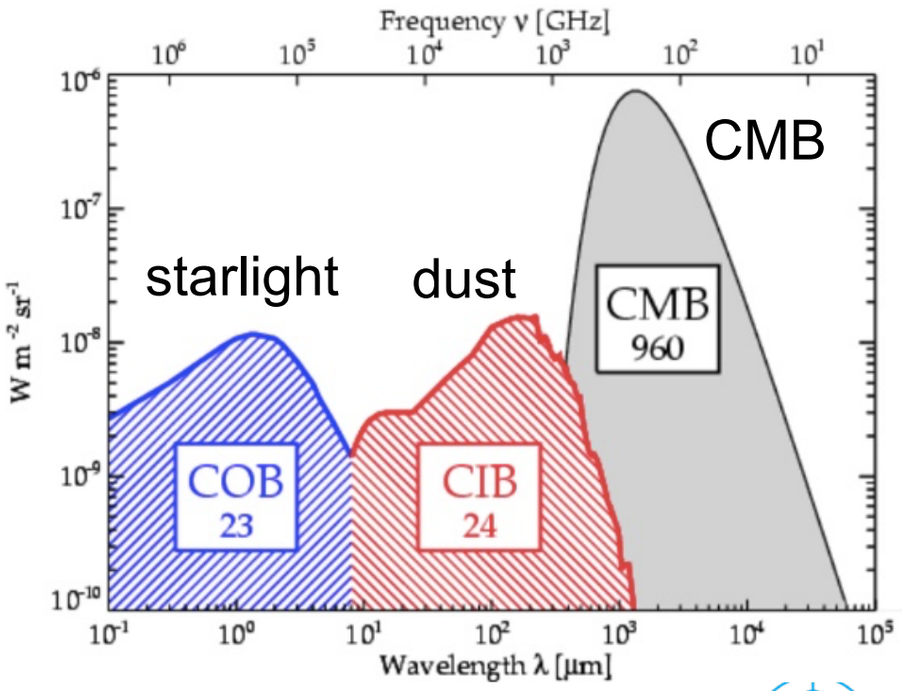
> Only neutrino telescopes can do **astronomy at PeV/EeV energies.**



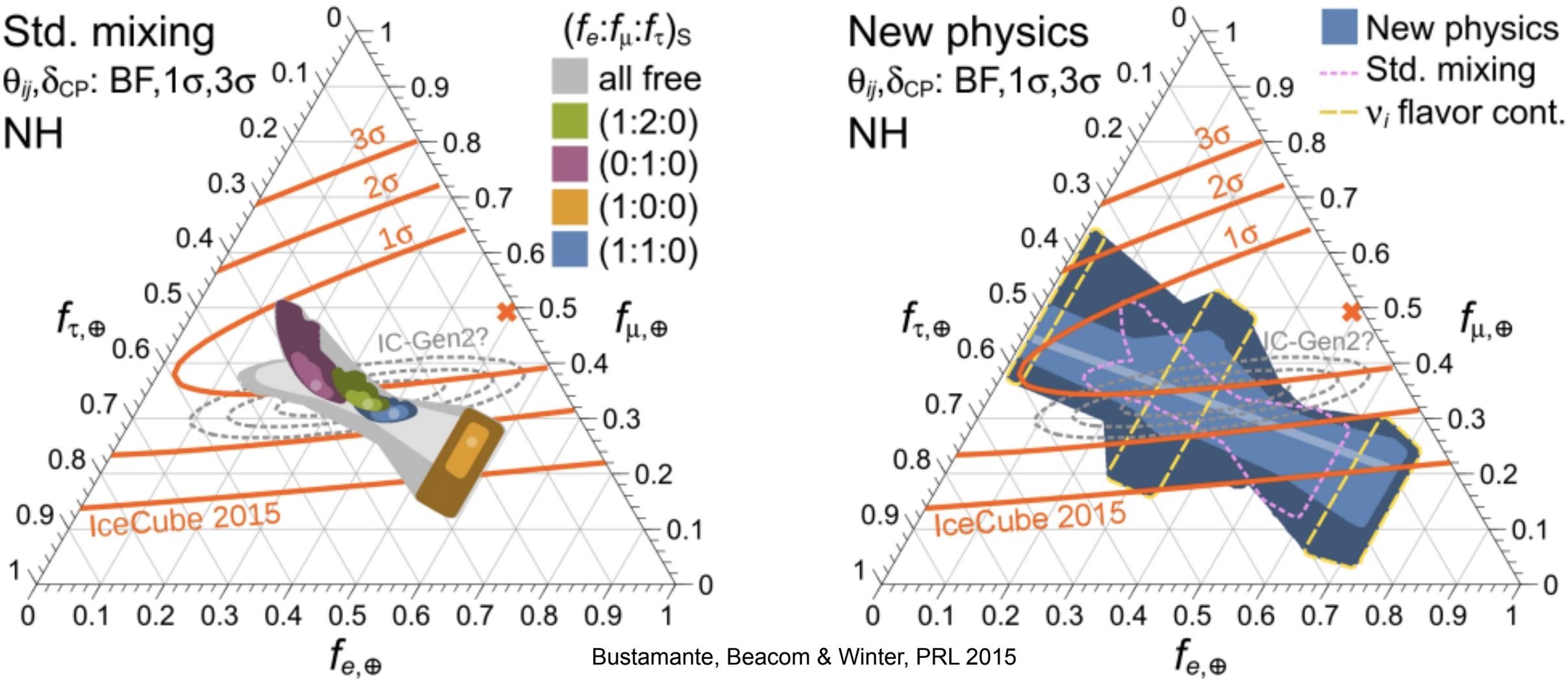


γ-ray horizon

Pair production in intergalactic photon fields



Neutrino flavors and astronomy.



Bustamante, Beacom & Winter, PRL 2015

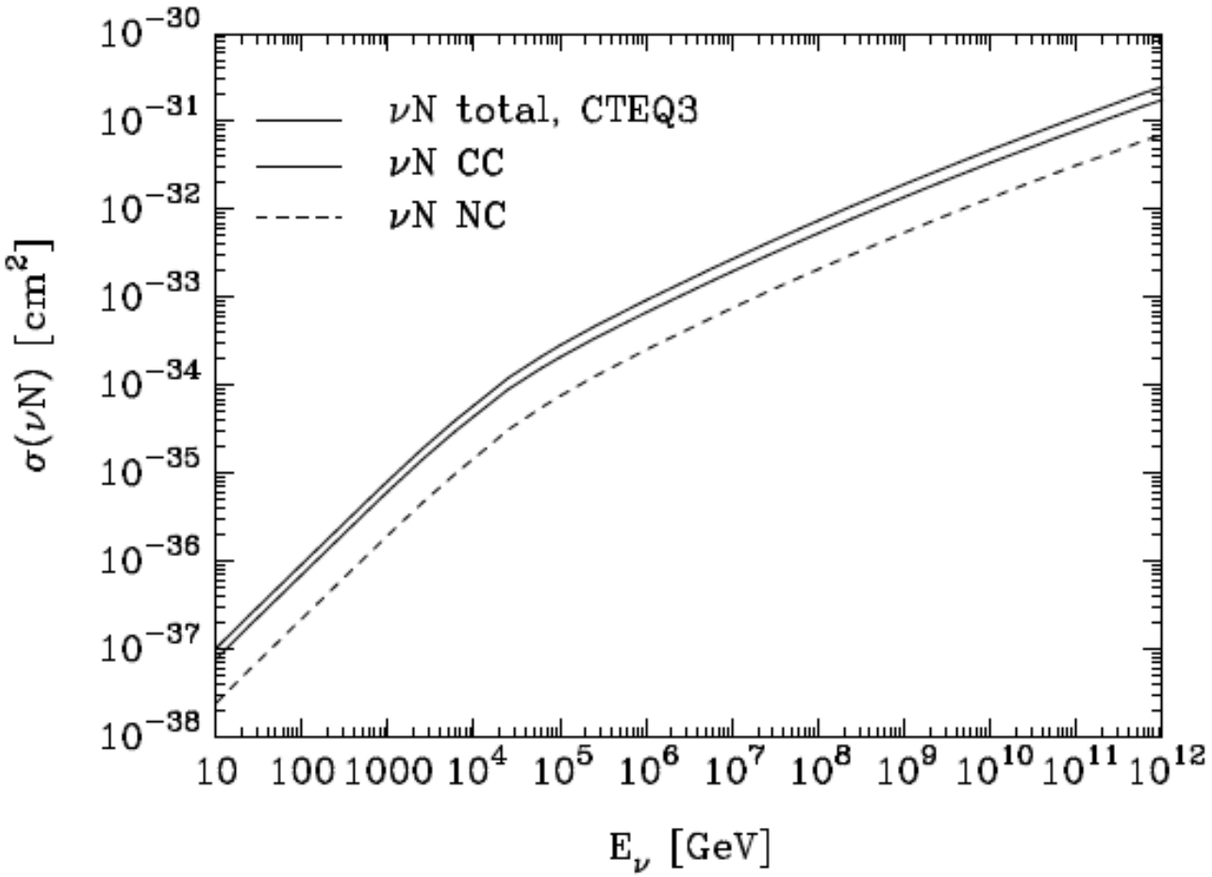
> Neutrinos carry flavor.

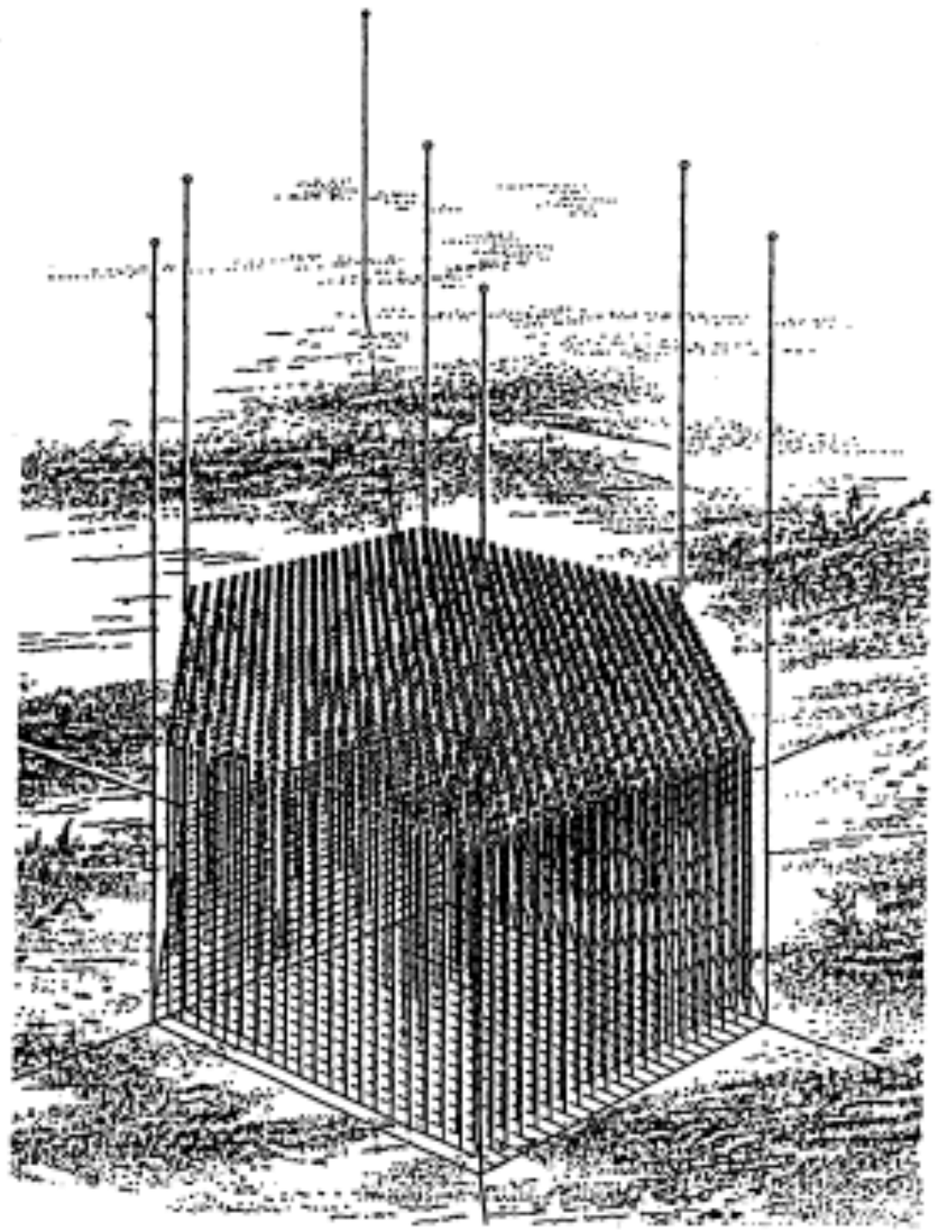
> **Flavor ratio** depends on **production mechanism / source environment**.

> Observations of an **unexpected flavor ratio** could identify **new physics.**

Neutrino astrophysics.

> **Small cross-section** of neutrinos requires **huge detectors.**



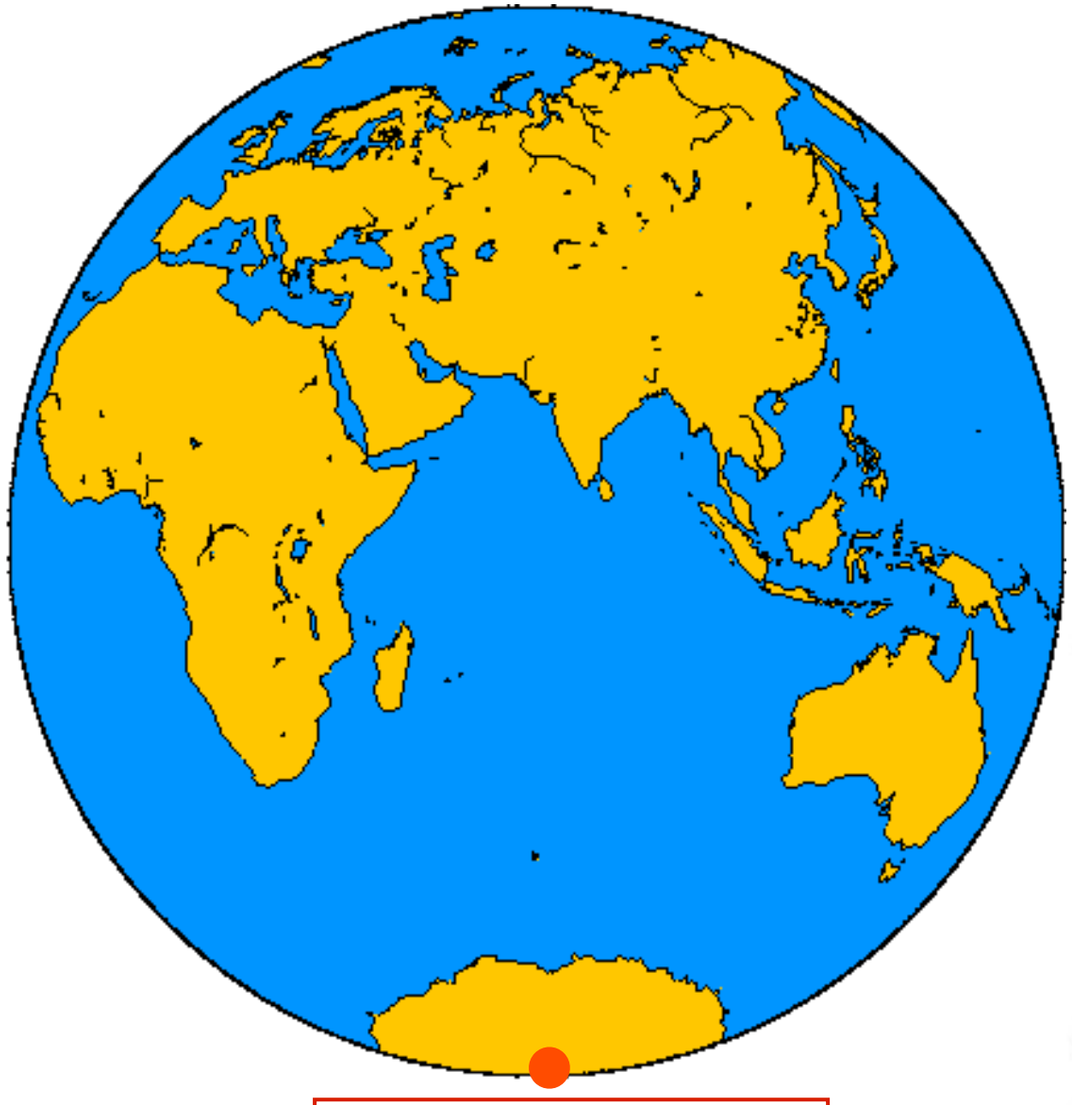


> **First design** of a **1 km³** underwater detector already in 1978

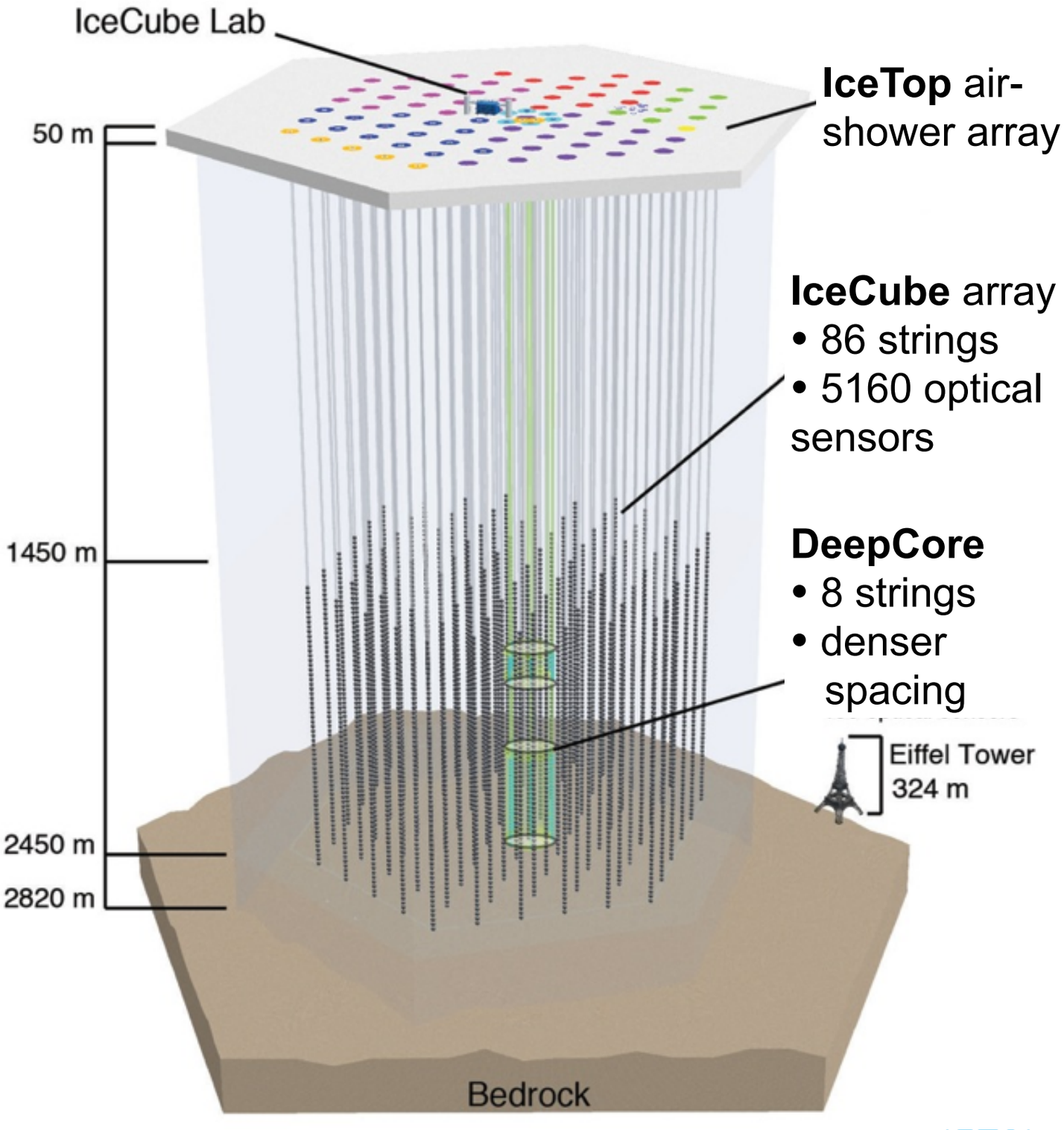
- DUMAND array off the coast of Hawaii
- Never built after first test strings failed

> **35 years later** we are finally there....

The IceCube neutrino telescope.

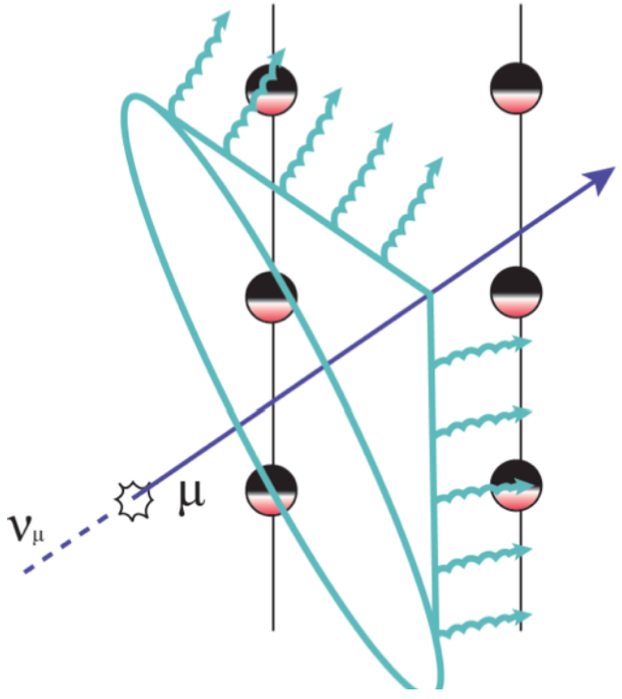


IceCube



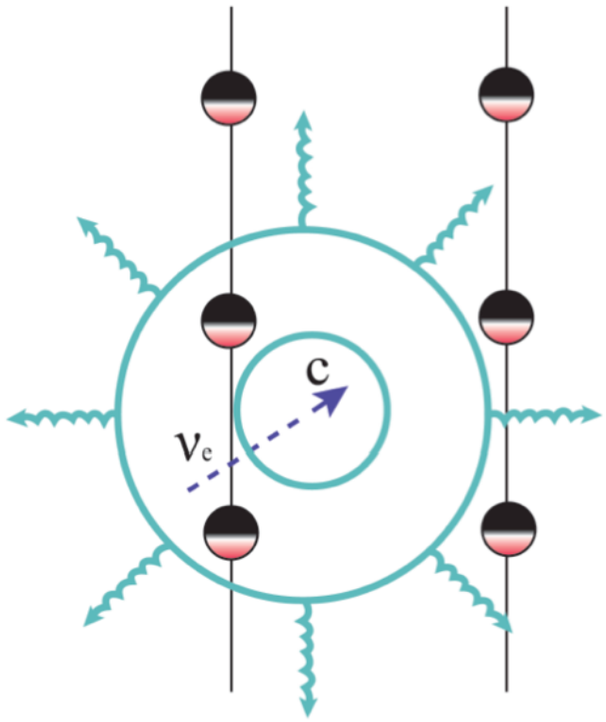
- **Completed** in Dec **2010**.
- Instrumented volume: **~ 1km³**

Neutrino detection by Cherenkov light.



> **Charged particles** produced in neutrino interactions emit **Cherenkov light**.

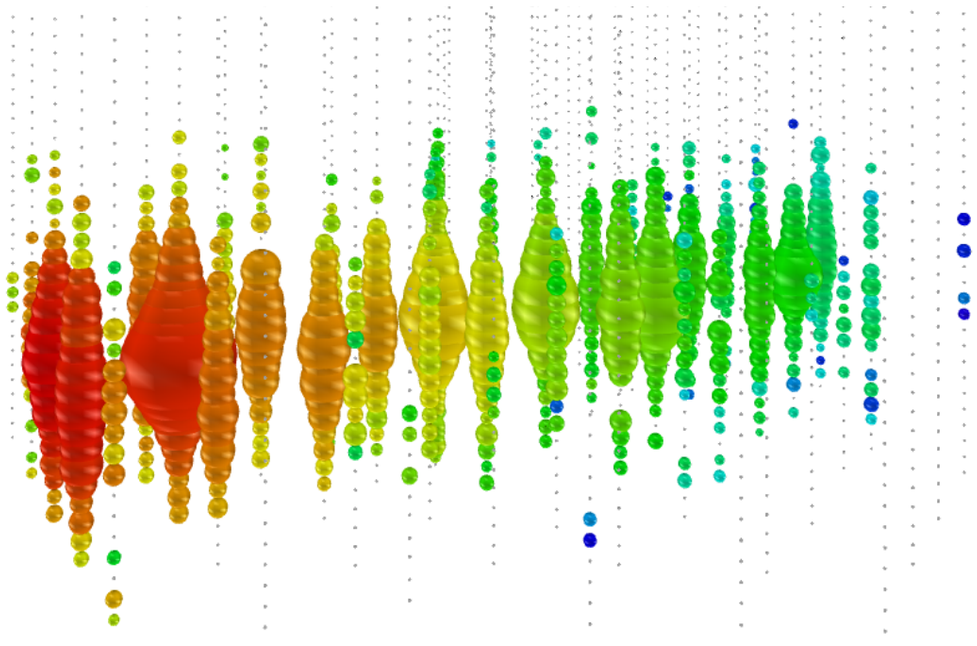
> **Optical sensors** deployed in **transparent medium** record arrival time and amplitude of light signal



> **Neutrino direction** from arrival time pattern

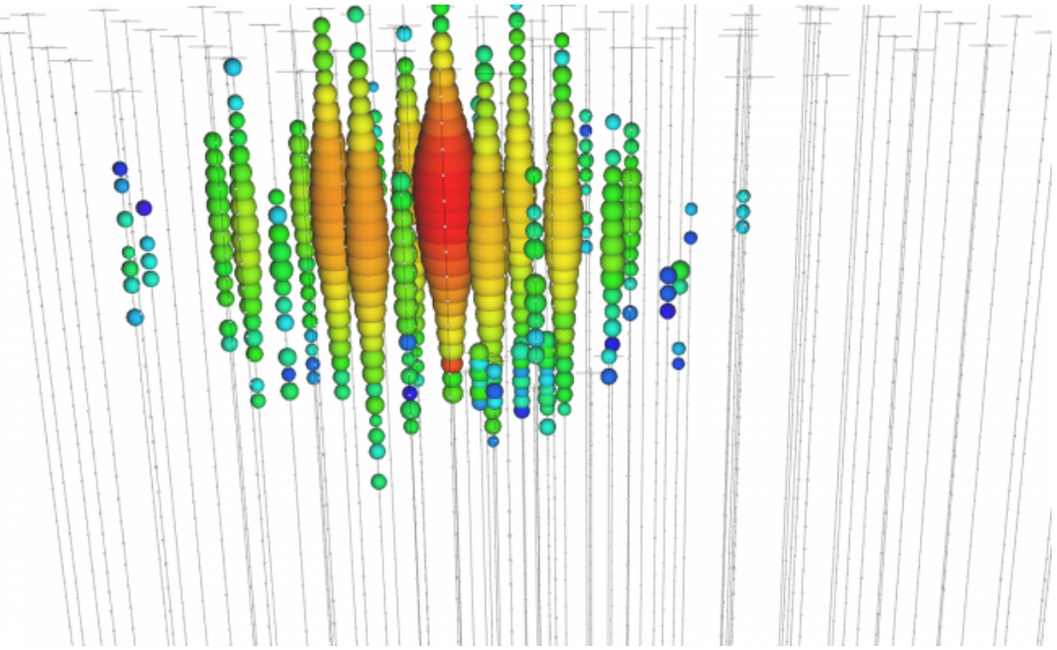
> **Neutrino energy** reconstruction from amplitude.

Detection of high-energy neutrinos.



> **Track-like event** signatures
(CC interactions of ν_μ)

- **Angular** resolution: < 1°
- Effective **volume:** up to tens of km³.
- **Energy** resolution: only indirect measure of μ energy.

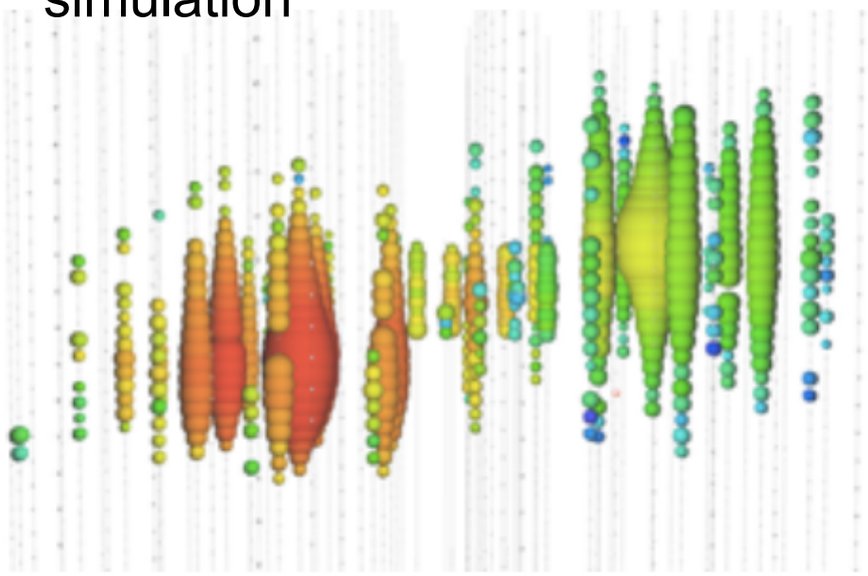


> **Shower-like event** signatures
(CC interactions of ν_e,ν_τ, NC interactions)

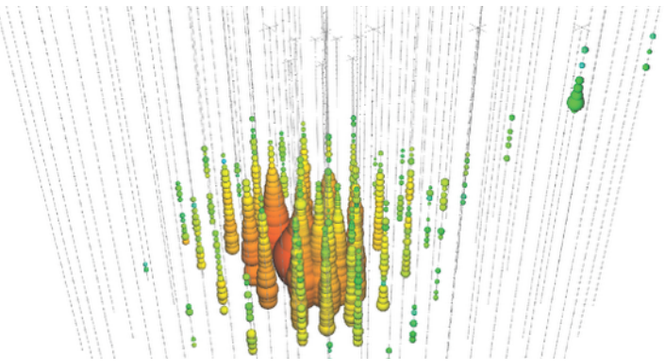
- **Angular** resolution: > 10°
- Effective **volume:** ~ 1 km³.
- **Energy** resolution: ~15% of deposited energy.

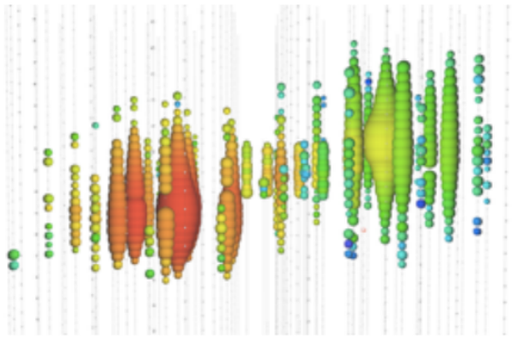
Detection of high-energy neutrinos.

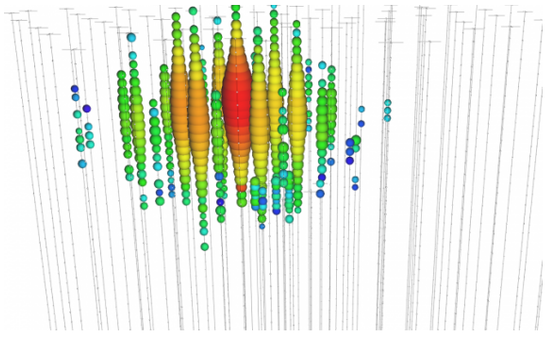
simulation



Early Late







> **High-energy ν_τ events**
(CC interactions ν_τ)

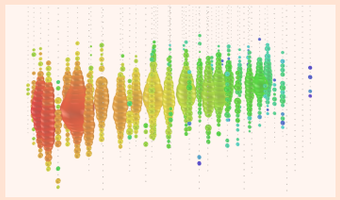
- ν_τ at PeV energies
- unique signatures that can identify a ν_τ interaction.

> **Starting events**
(all flavors)

- **Angular** resolution: < 1° - 15°
- Effective **volume:** <~ 0.5 km^3
- **Energy** resolution: ~15% of deposited energy.

Neutrino flavors and event signatures.

ν_μ

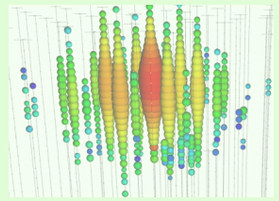


tracks

- high statistics
- high background
- good resolution

ν_e, ν_μ, ν_τ

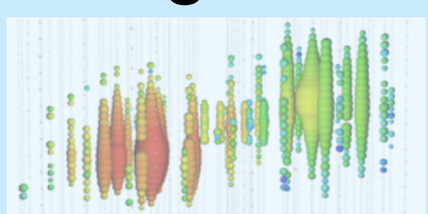
showers



- high statistics
- low background
- bad resolution

starting events

tau signatures

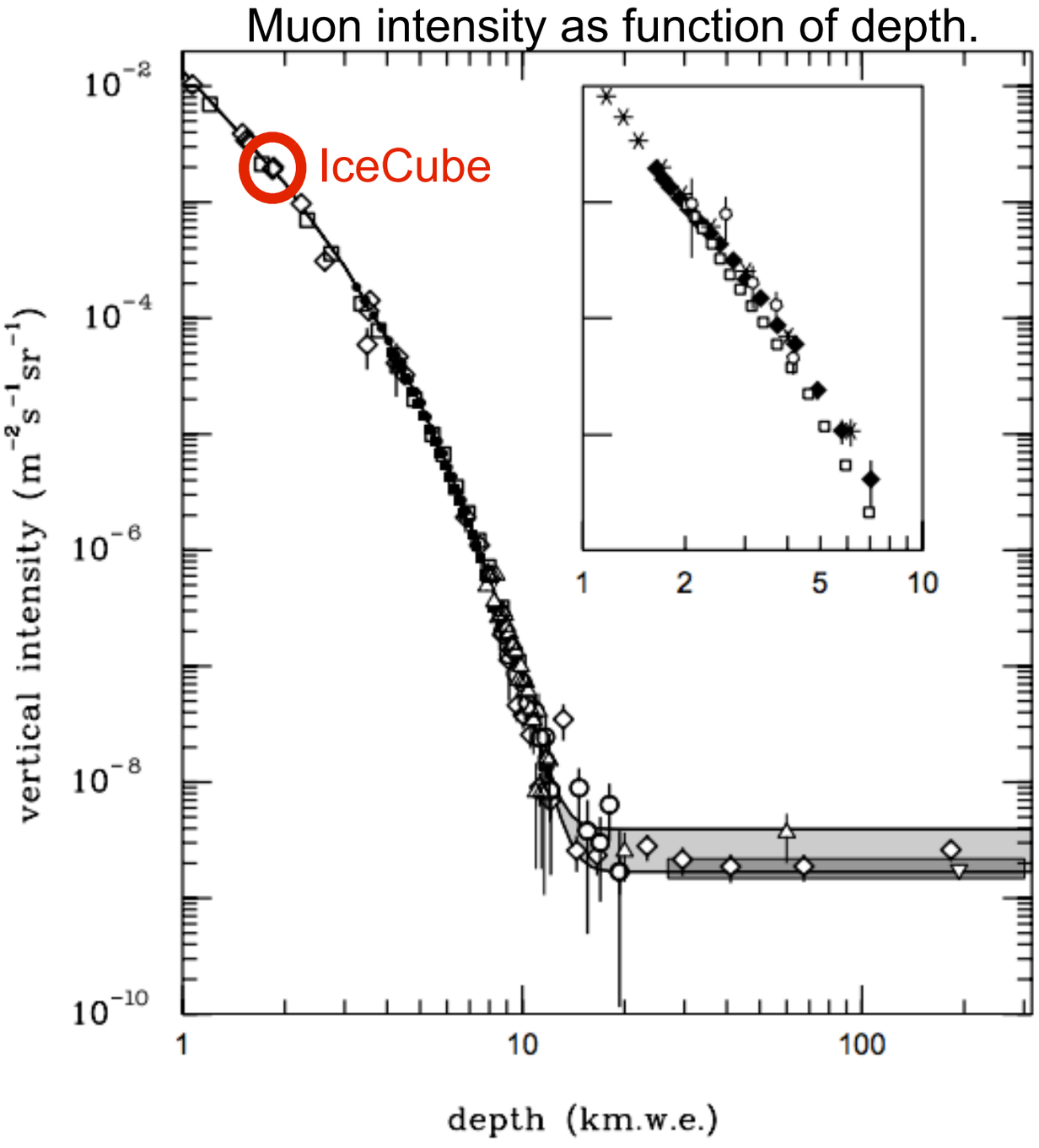


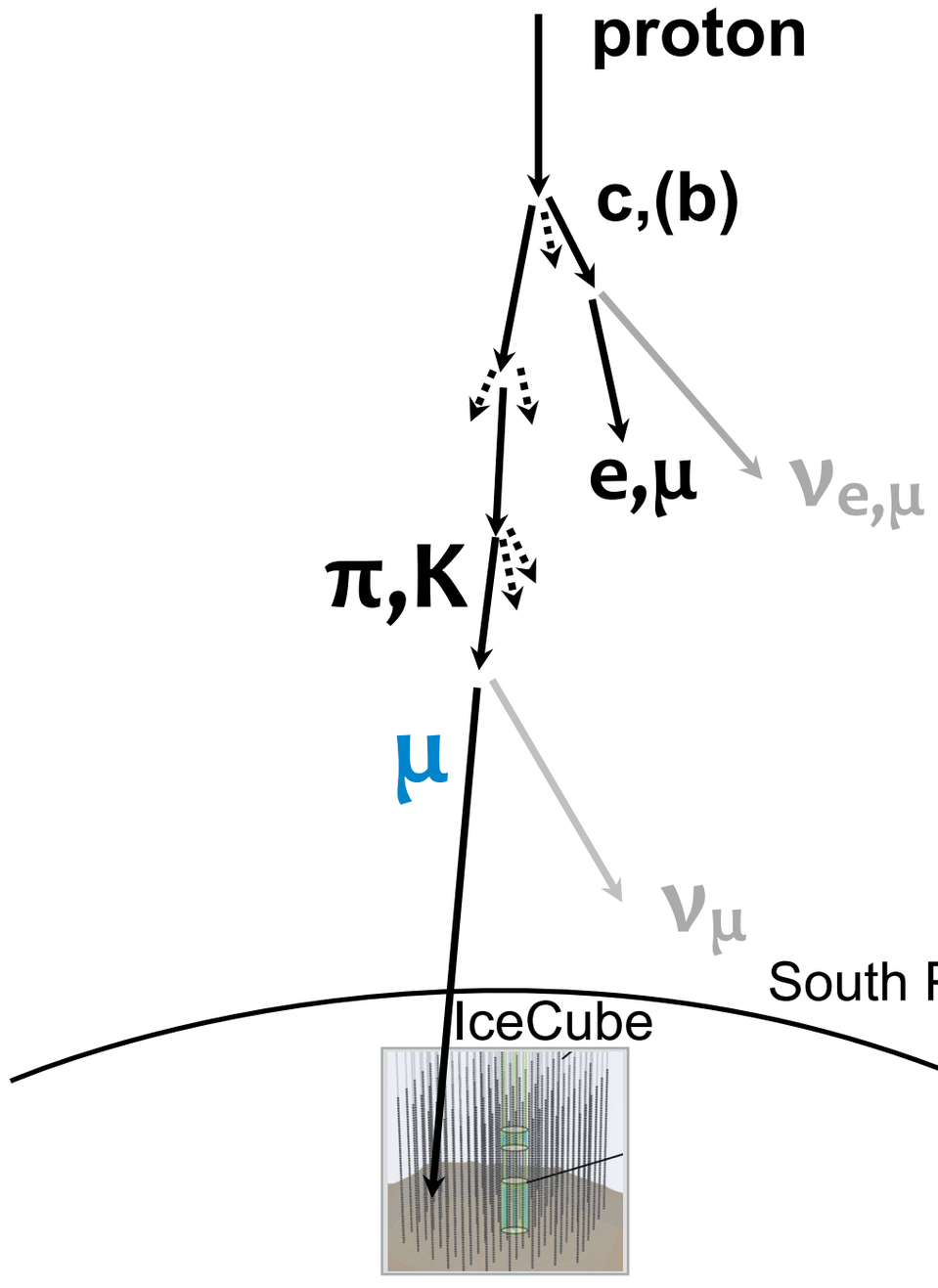
- very low statistics
- very low background

ν_τ

The challenge: Atmospheric backgrounds.

- **Muons from CR air showers** account for 99.9999% of all events seen by IceCube.
- Restricted to **Southern hemisphere.**





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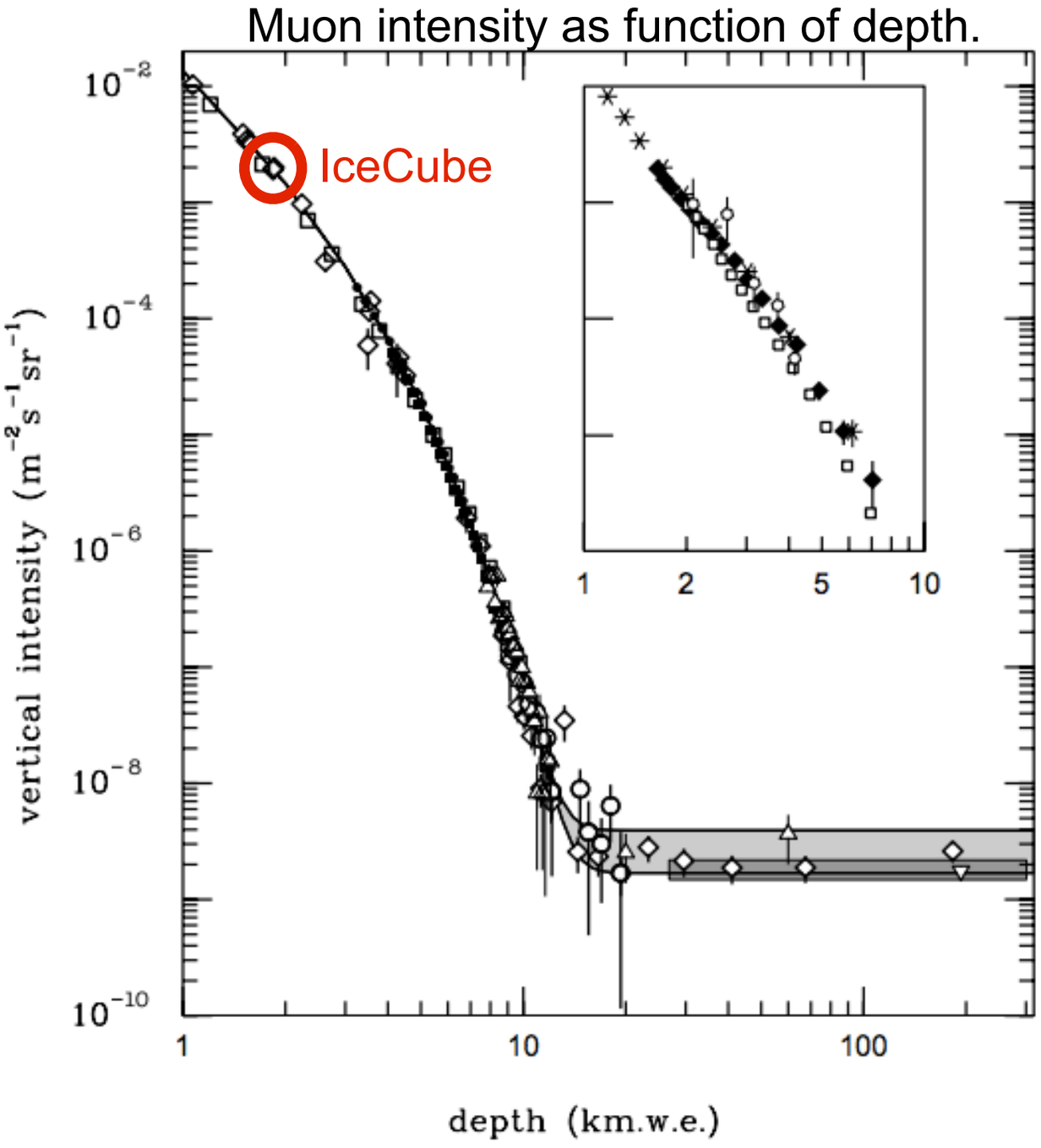
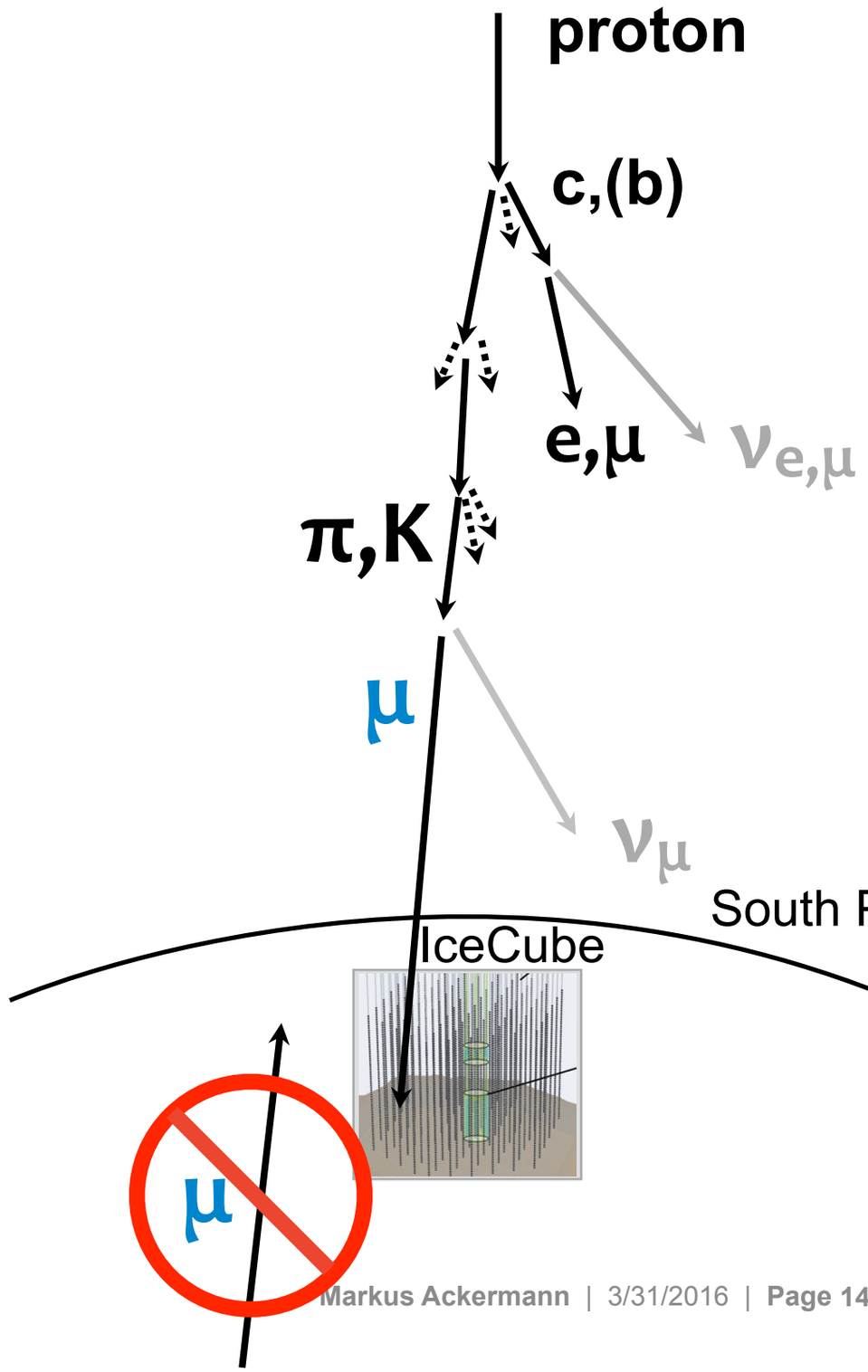
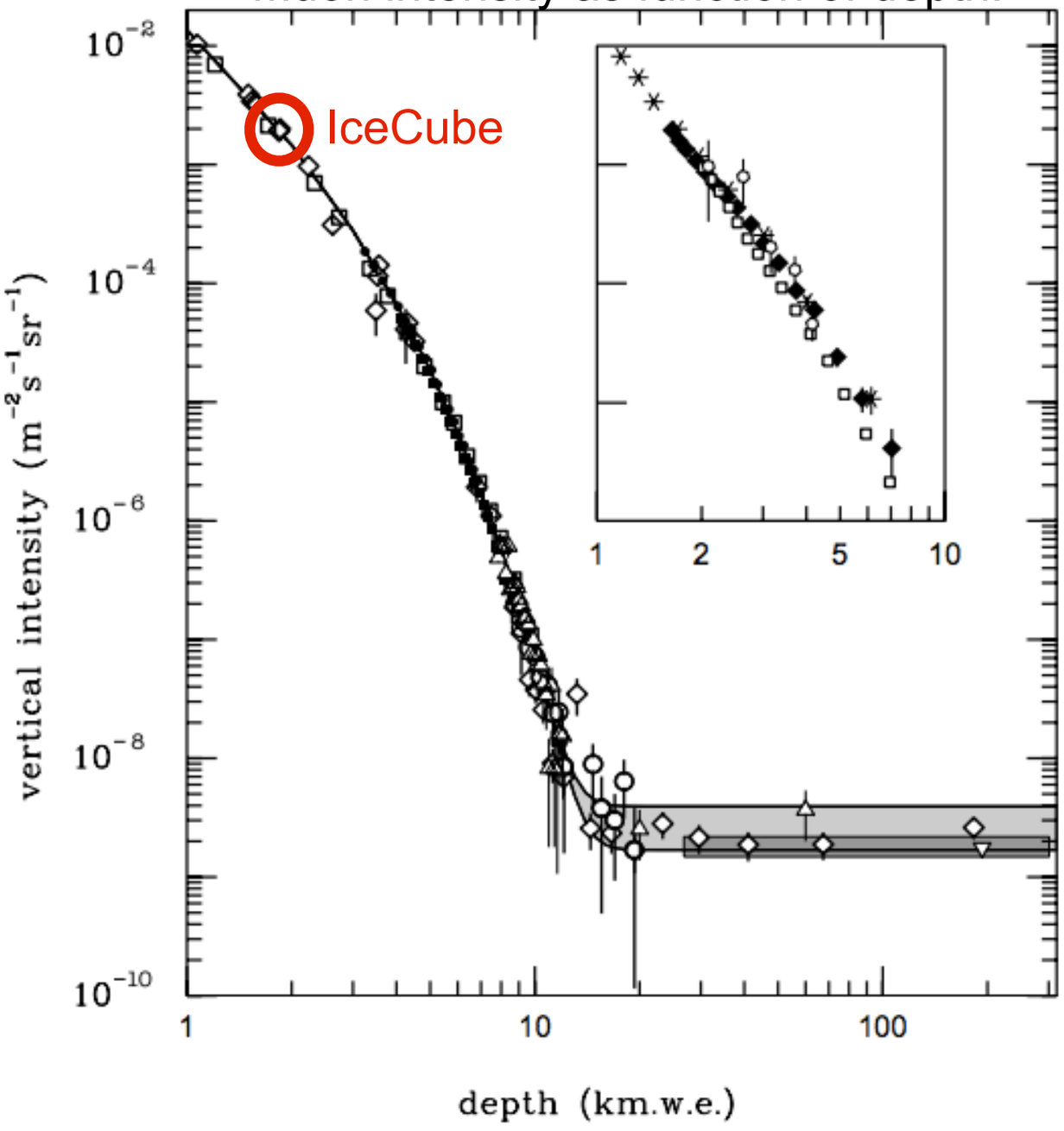


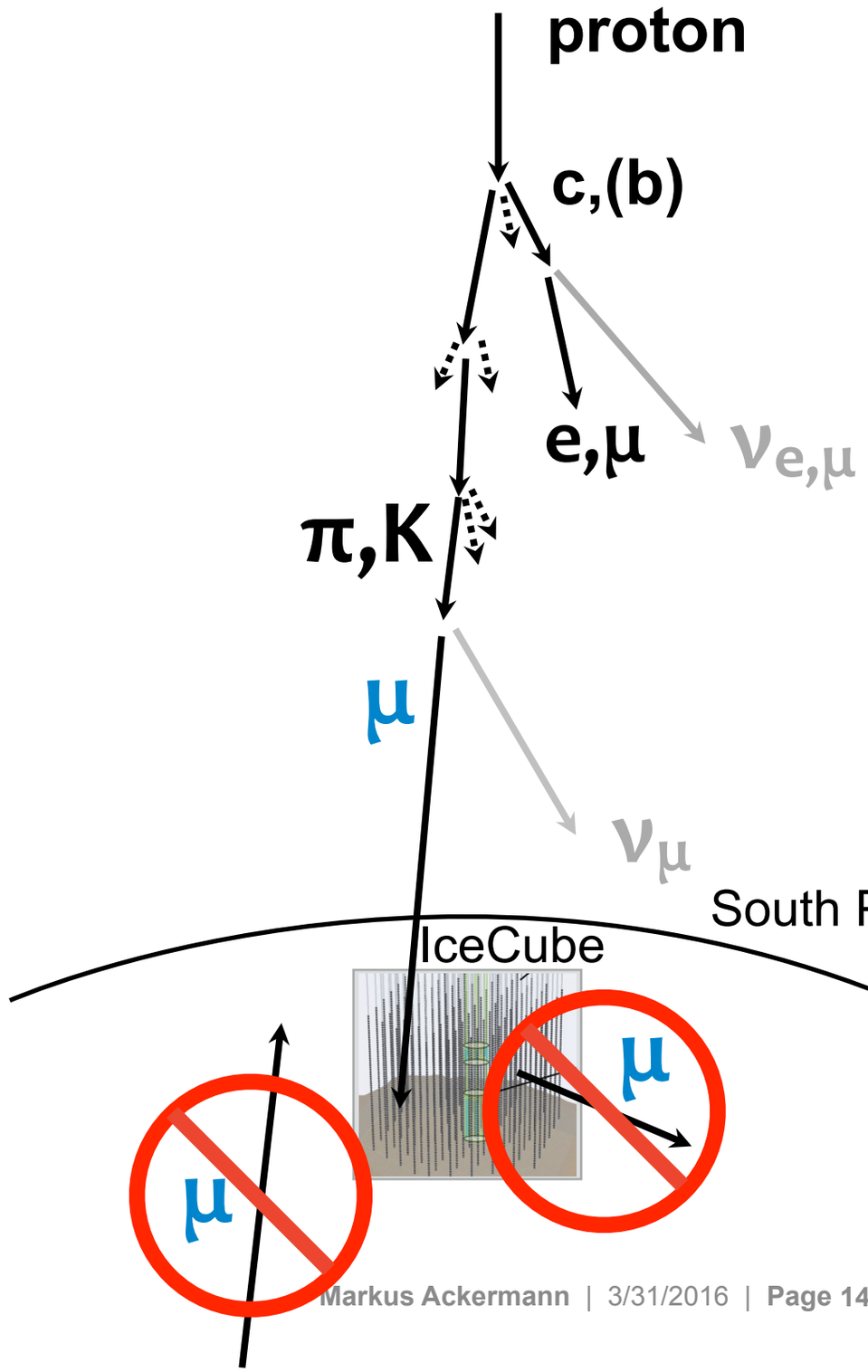


The challenge: Atmospheric backgrounds.

- **Muons from CR air showers** account for 99.9999% of all events seen by IceCube.
- Restricted to **Southern hemisphere.**

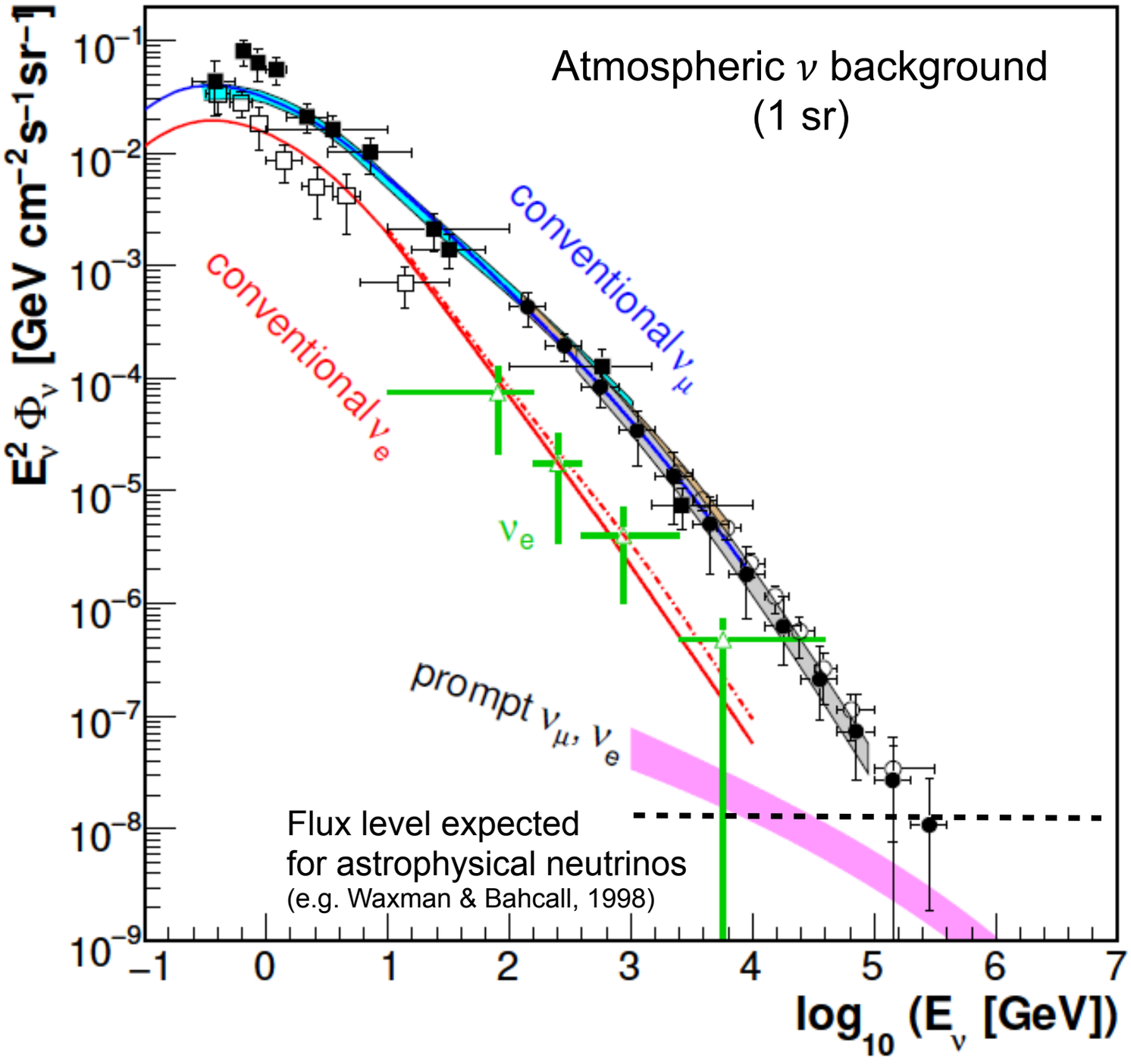
Muon intensity as function of depth.

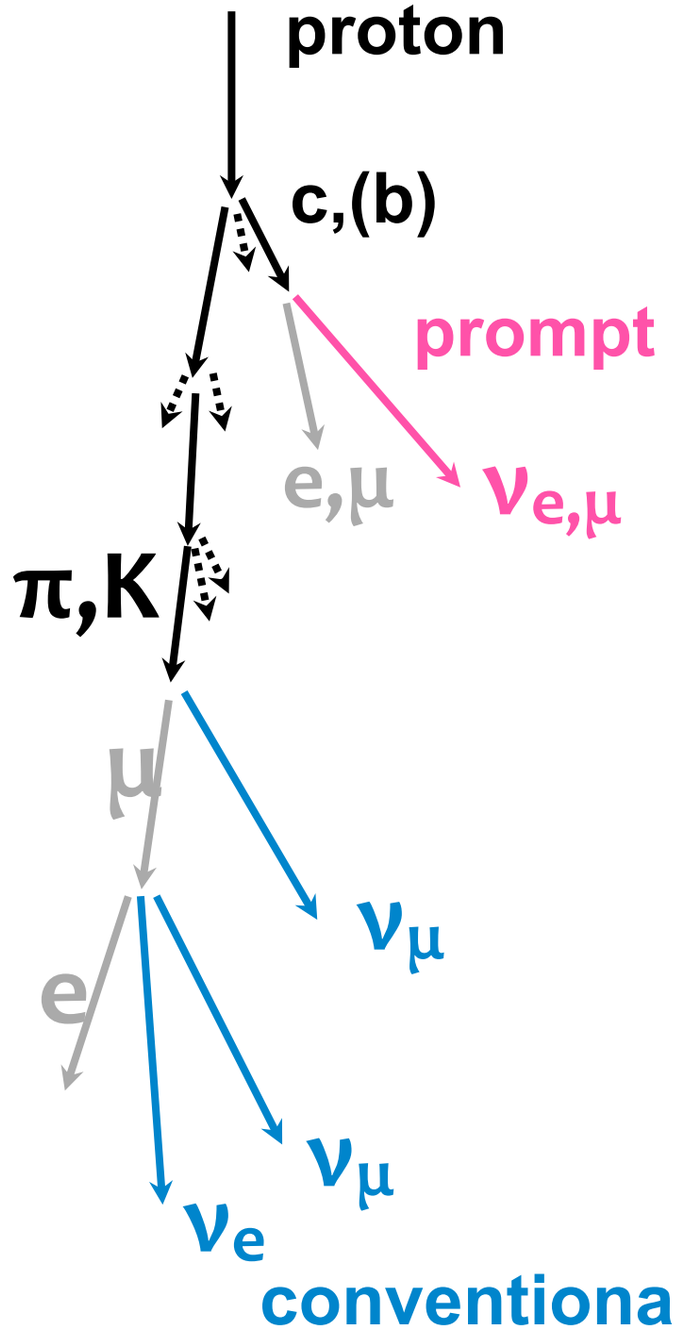




The challenge: Atmospheric backgrounds.

- **Most neutrinos** seen by neutrino telescopes are of **atmospheric origin**.
- Atmospheric-ν are produced in **CR air shower interactions**.



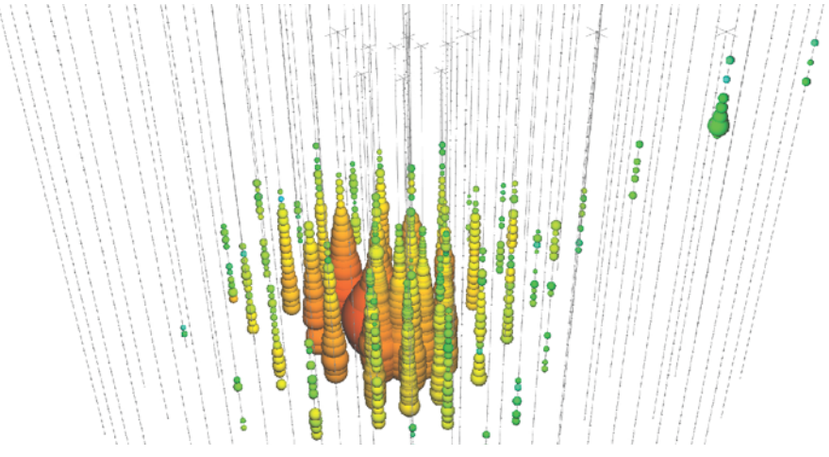


The golden channel: Starting events

ν_μ

tracks

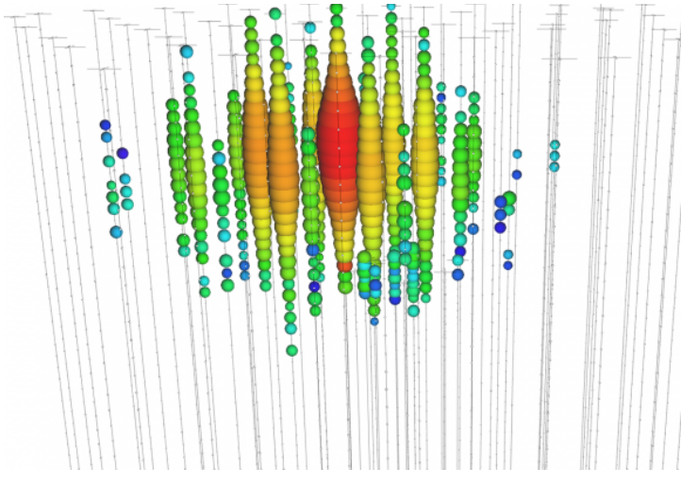
- high statistics
- high background
- good resolution



ν_e, ν_μ, ν_τ

showers

- high statistics
- low background
- bad resolution



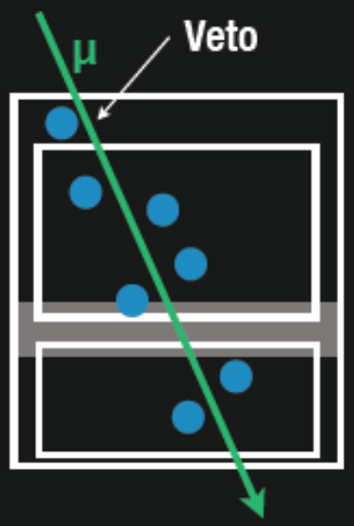
starting events

tau signatures

- very low statistics
- very low background

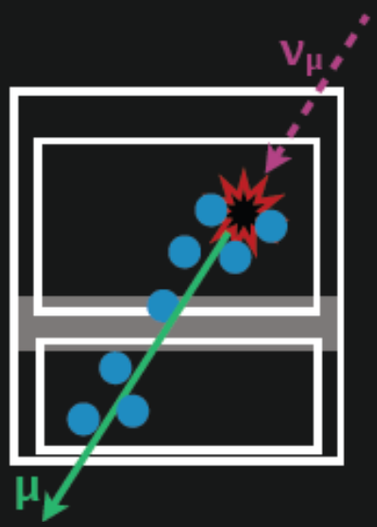
ν_τ

Neutrino induced showers and starting tracks…



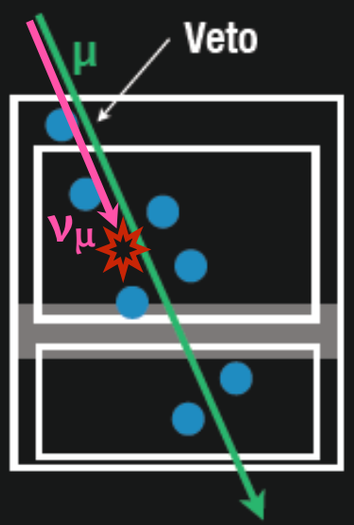
> Atmospheric muons

- Only from the surface (Southern hemisphere).
- Produce light in veto region.



> Astrophysical neutrinos

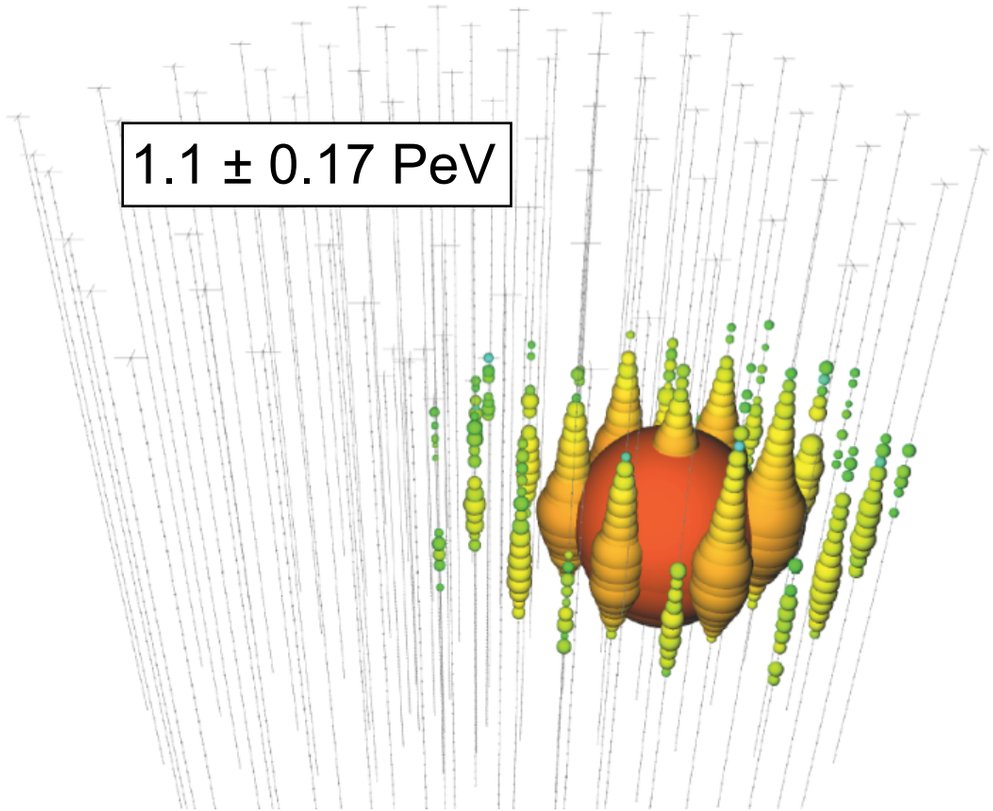
- No light in veto region.
- Compact shower or emerging track
- From both hemispheres.

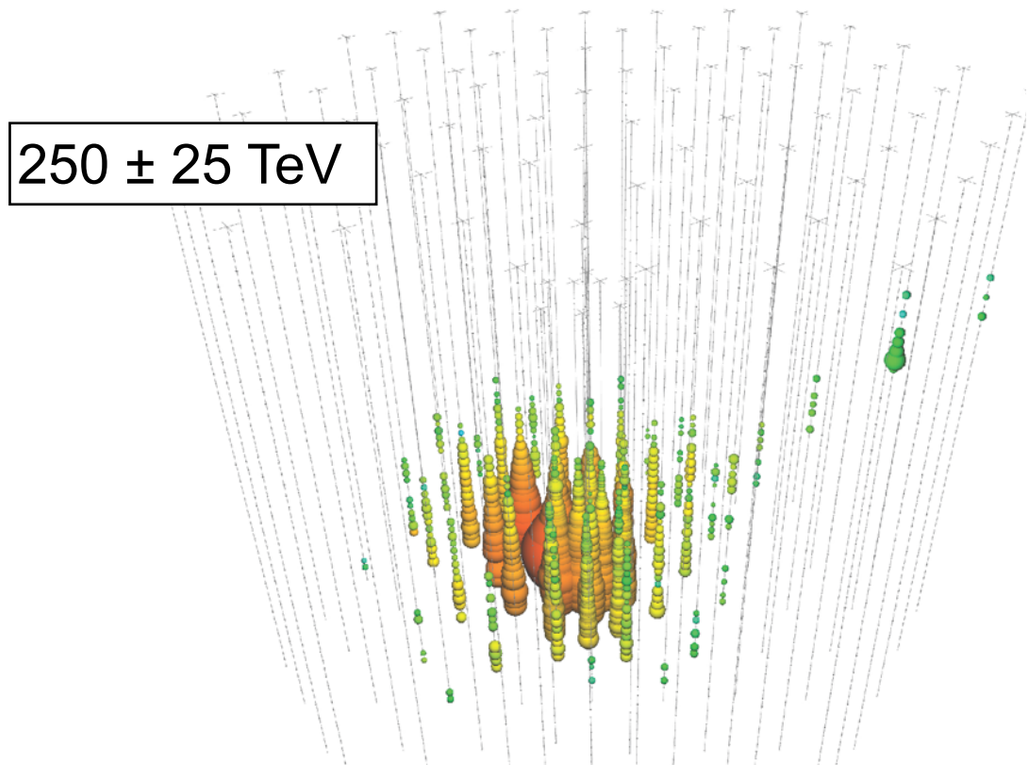


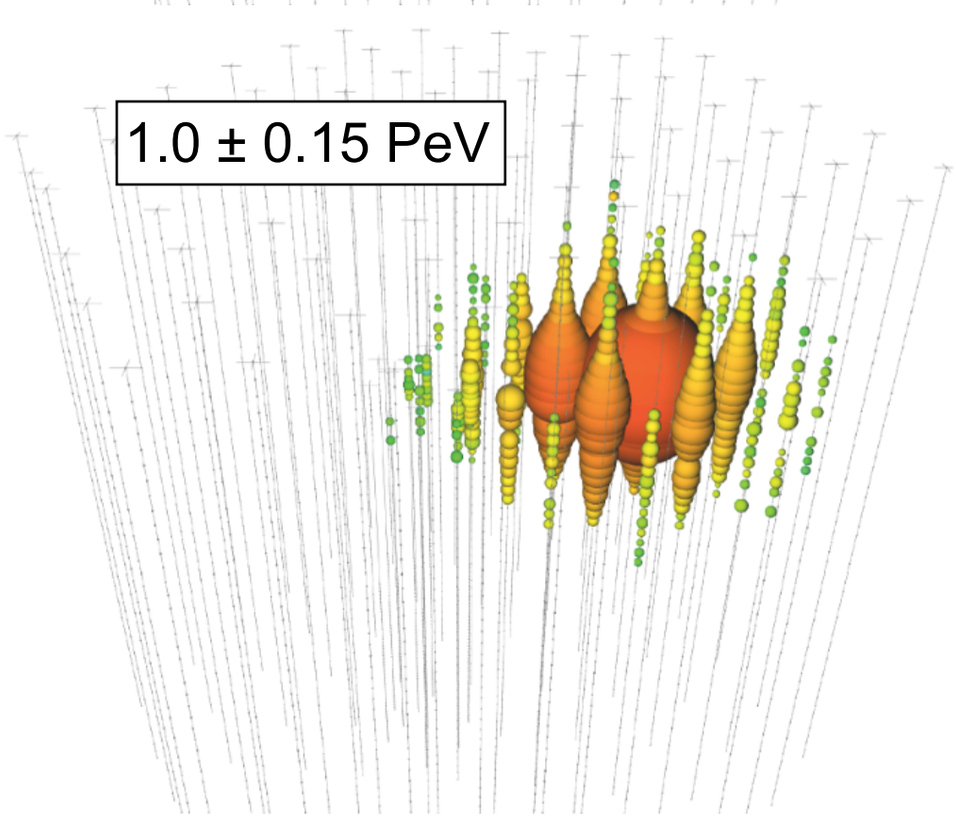
> Atmospheric neutrinos

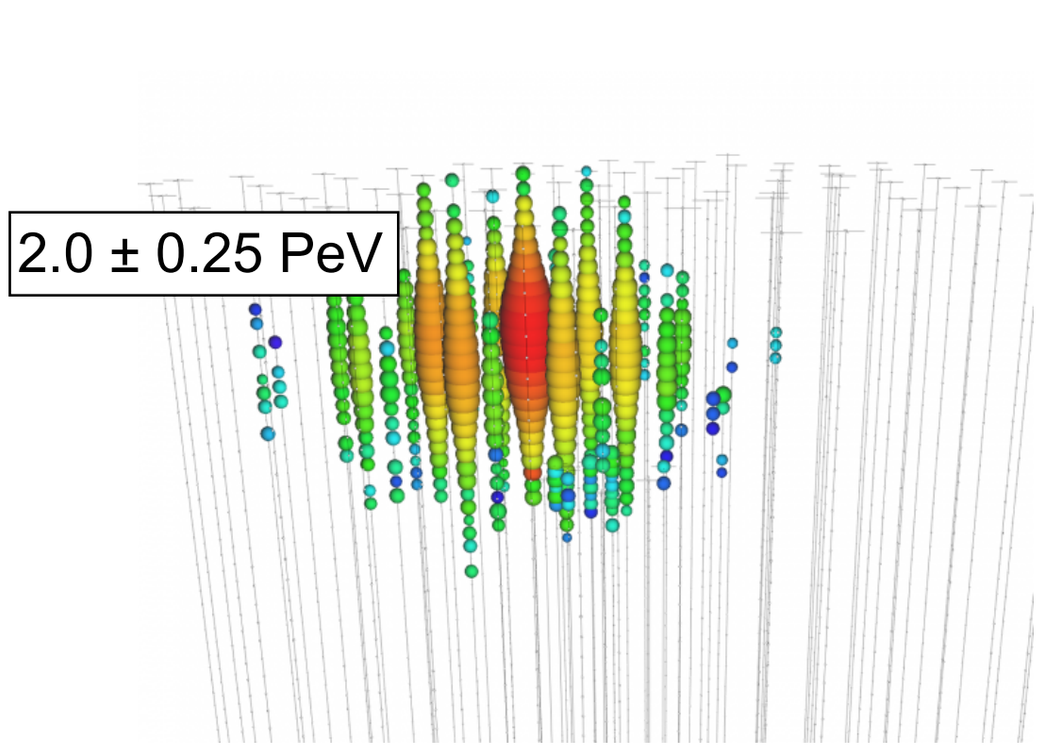
- likely accompanied by muon if produced by CR over the Southern hemisphere.
- Muon produces light in veto region

… lead to the discovery of cosmic neutrinos.

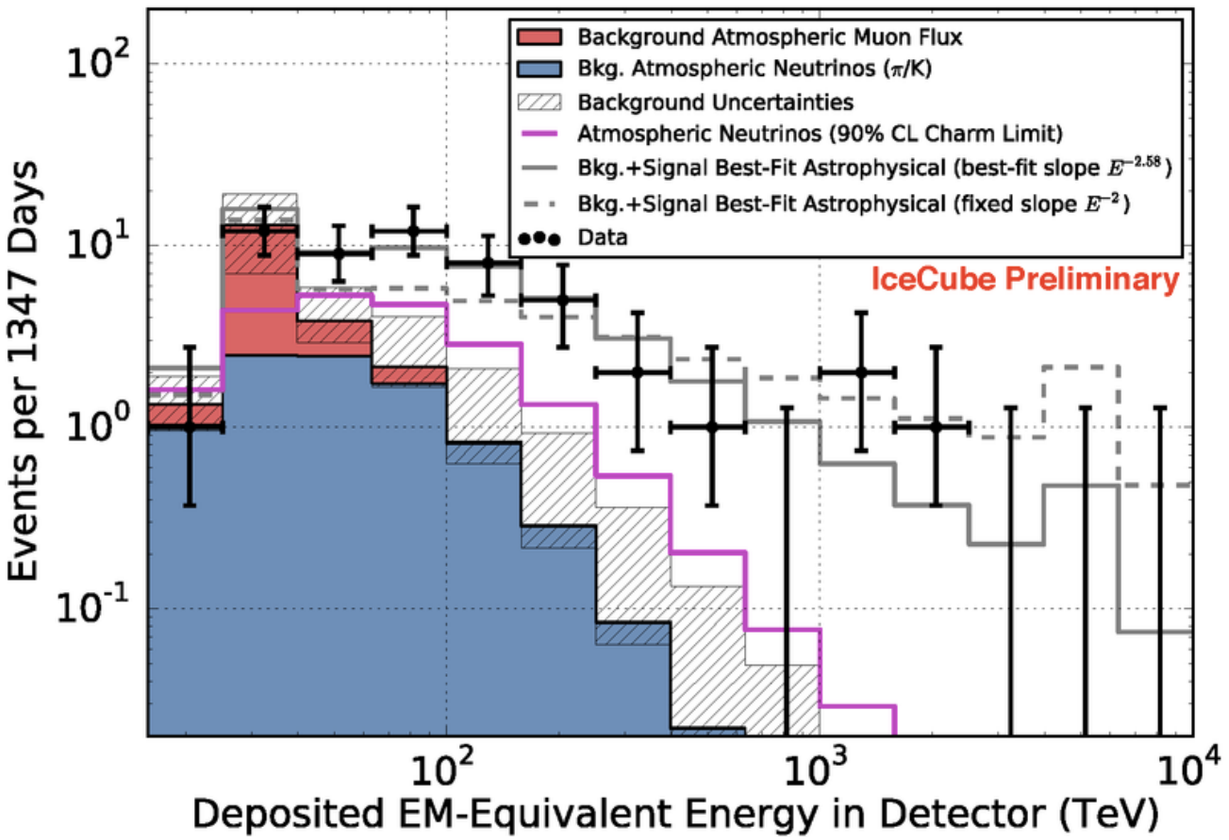


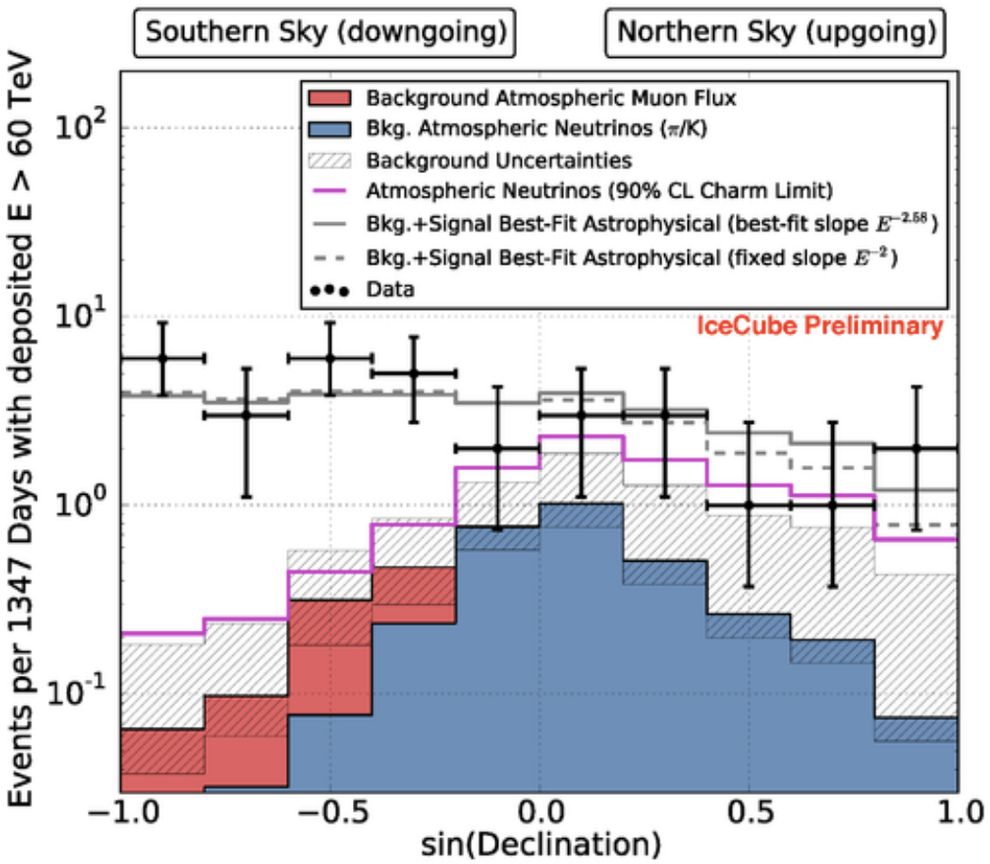






Observed events.

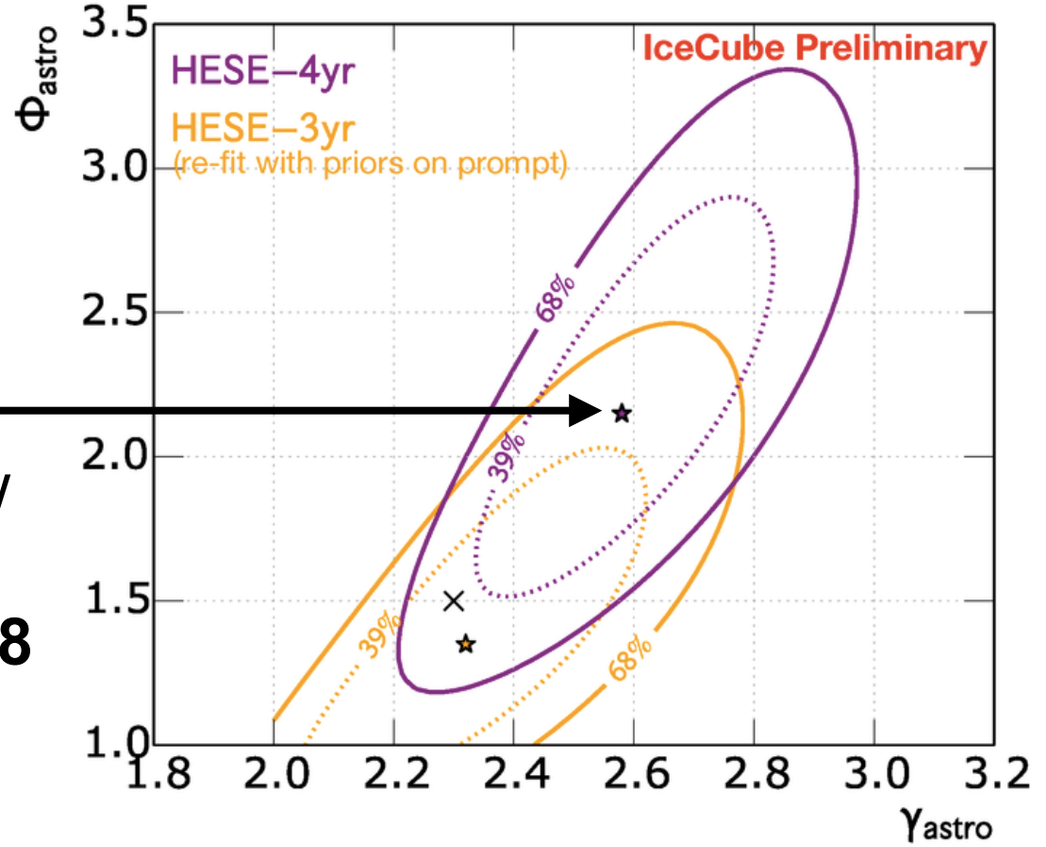




- **1347 days** observation time (May 2010 - Apr 2014)
- **54 events** above ~ 30 TeV energy detected.
- 3 events with energies **> 1 PeV**.
- **>5.7σ** statistical significance (we stopped counting…)

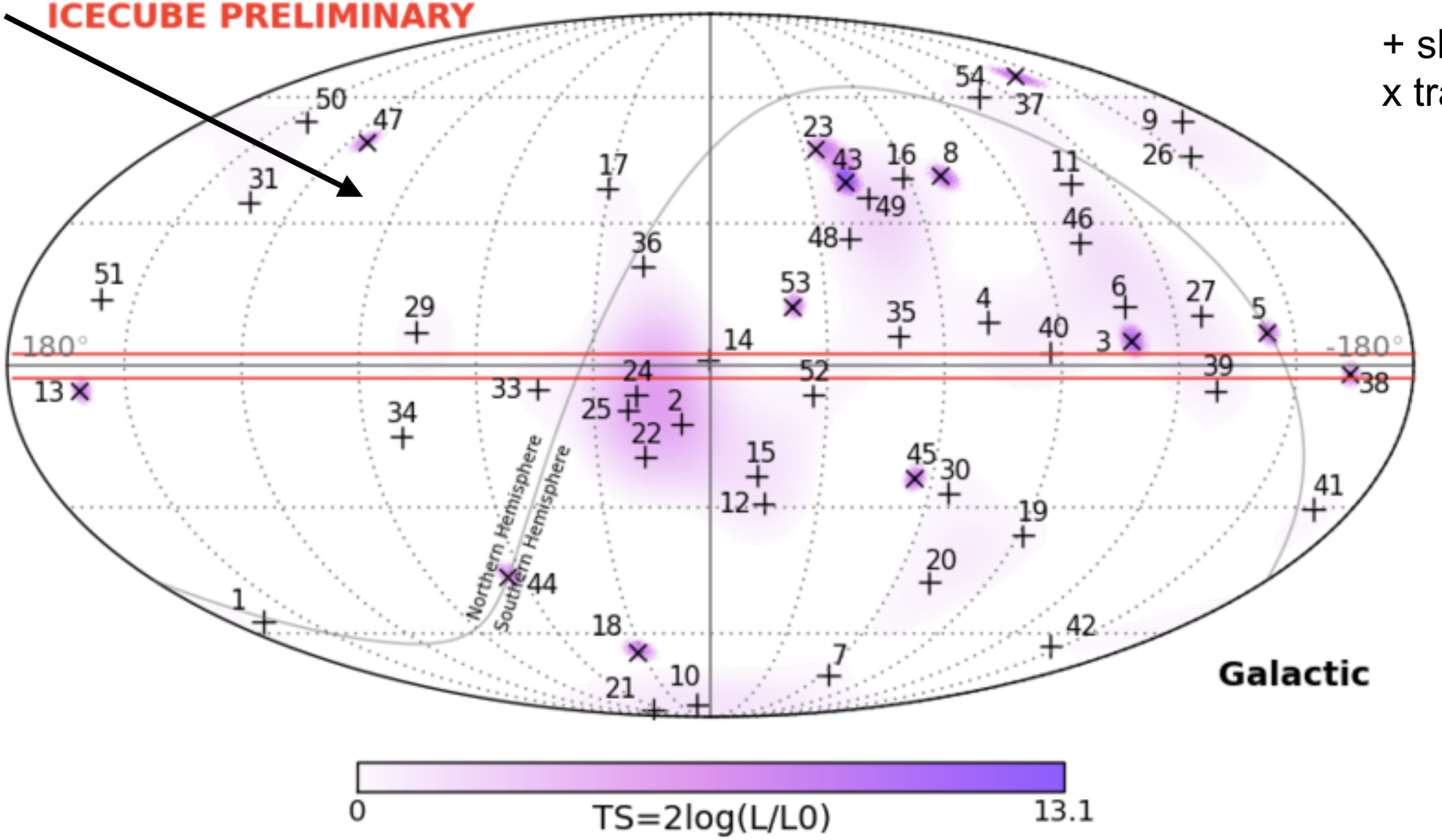
best-fit

power-law spectral index: **2.58**



Distribution on the sky.

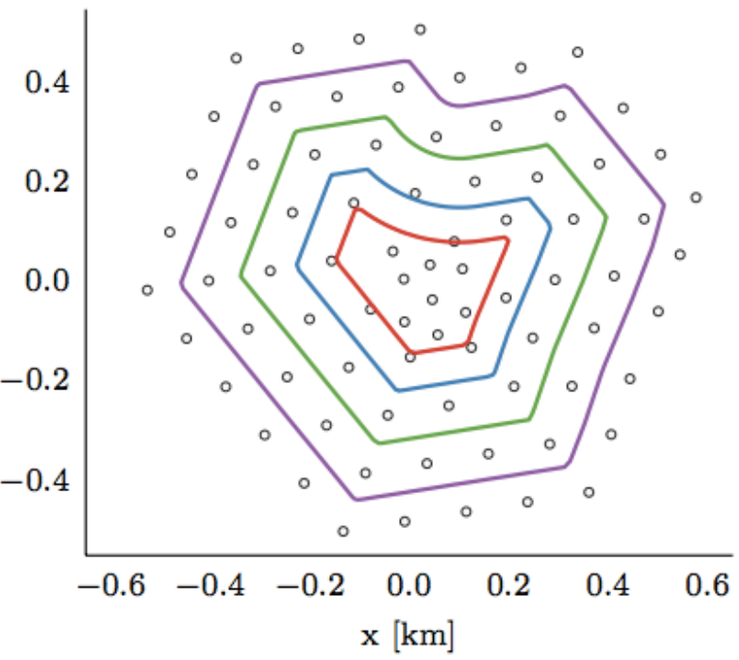
Earth absorbs ≳ 100 TeV neutrinos



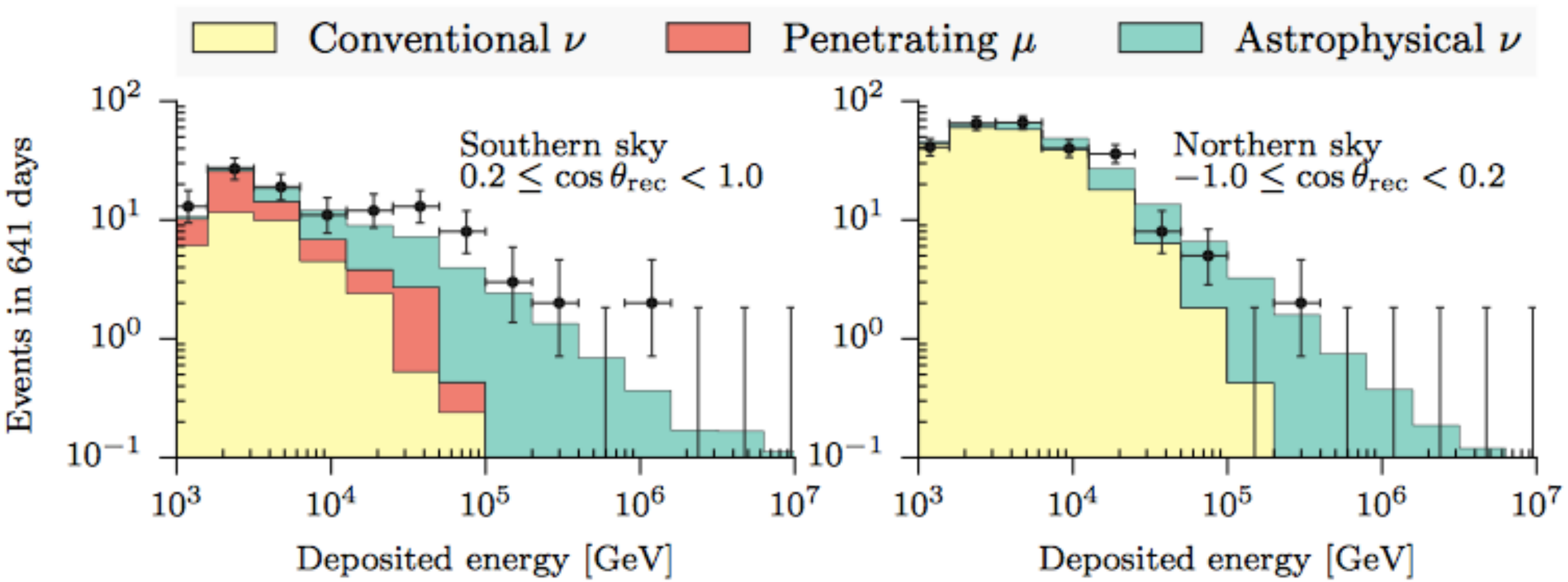
> Events from **high Galactic latitudes observed**.

> Event distribution is **compatible** with an **isotropic neutrino flux**.

Starting events at lower energies.

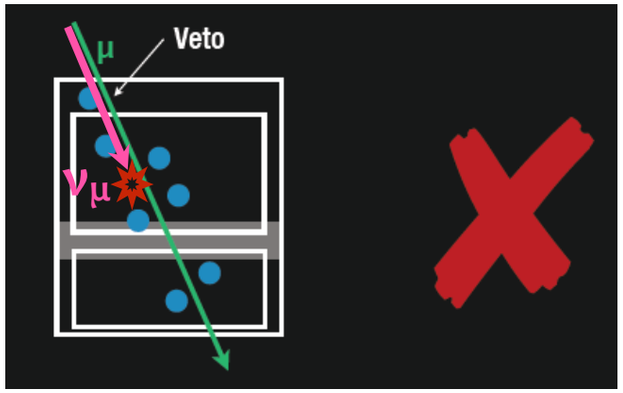


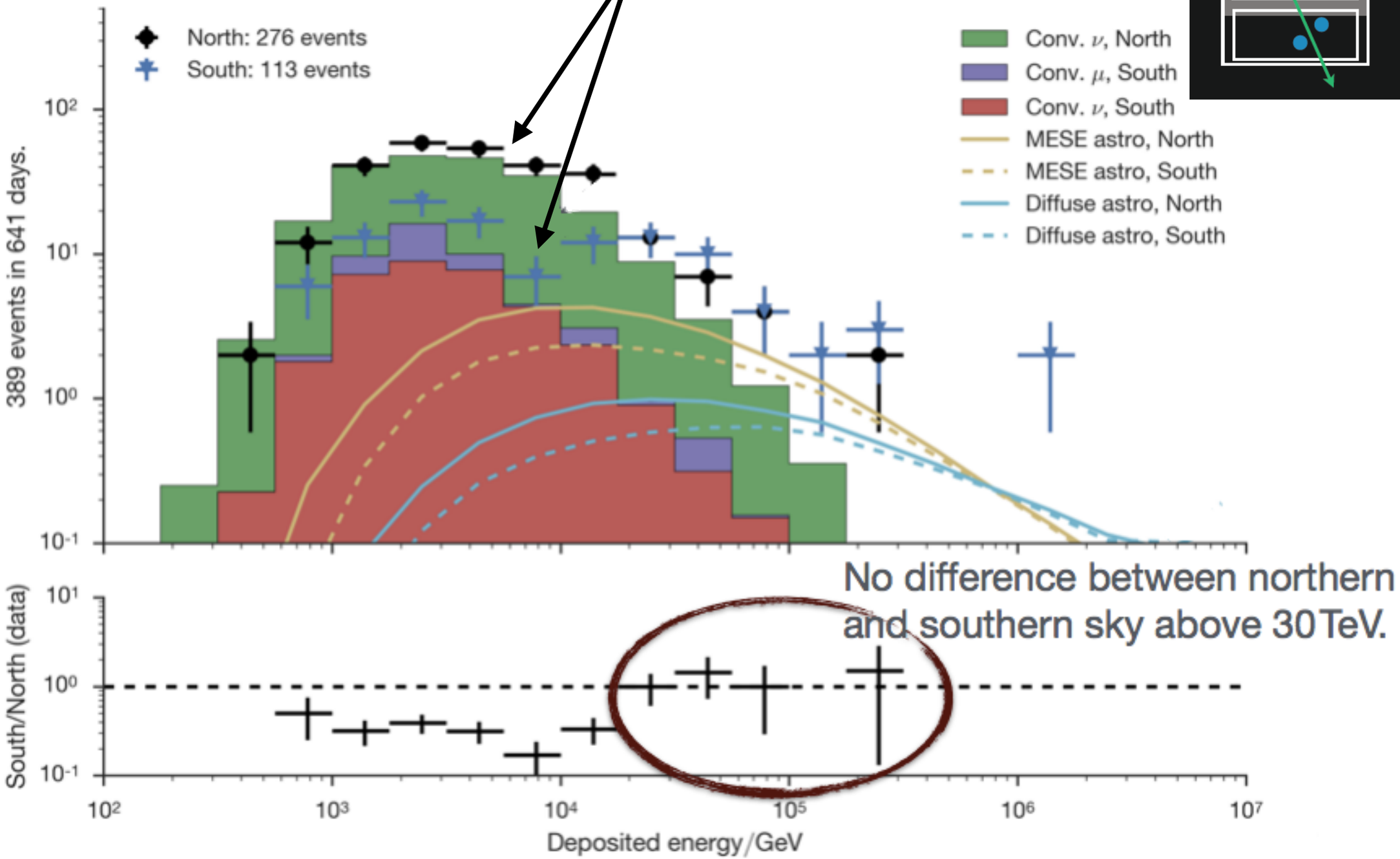
- Enlarge veto region to extend energy range below 30 TeV
- So far only applied to 2 years of IceCube data.
- Clear evidence for astrophysical neutrinos to energies ~ 10 TeV
- Best-fit spectral index: **2.5 ± 0.12**



Effects of the atmospheric neutrino veto.

Background from Southern hemisphere suppressed
by self-veto of atmospheric neutrinos





No difference between northern
and southern sky above 30 TeV.

The golden channel: Starting events

ν_μ

tracks

- high statistics
- high background
- good resolution

ν_e, ν_μ, ν_τ

showers

- high statistics
- low background
- bad resolution

starting events

Discovery of cosmic neutrinos above ~10 TeV

tau signatures

- very low statistics
- very low background

ν_τ

More statistics: Contained / non-contained shower events

ν_μ

tracks

- high statistics
- high background
- good resolution

ν_e, ν_μ, ν_τ

showers

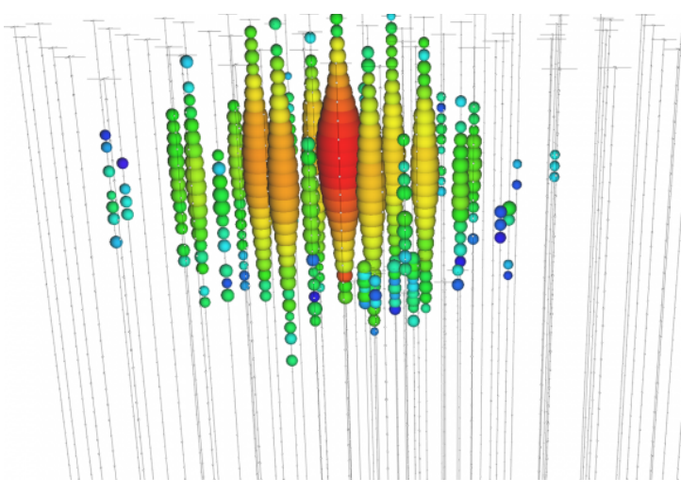
- high statistics
- low background
- bad resolution

starting events

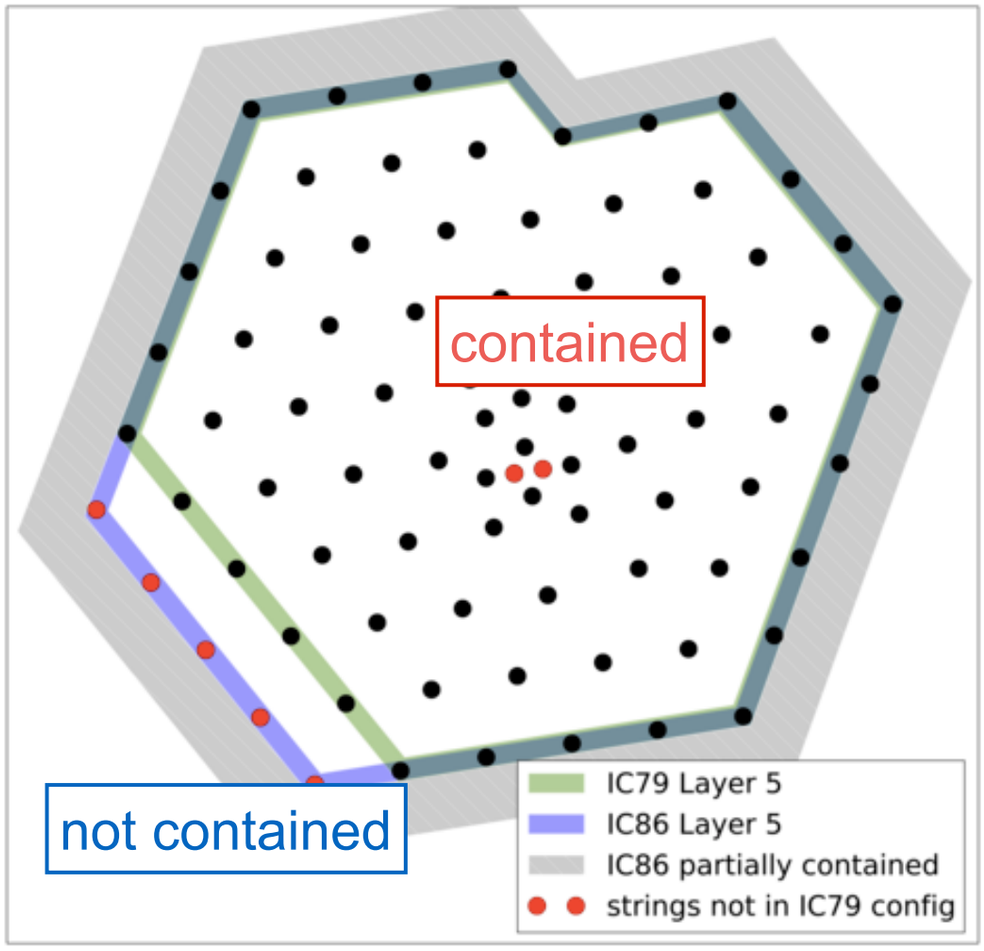
tau signatures

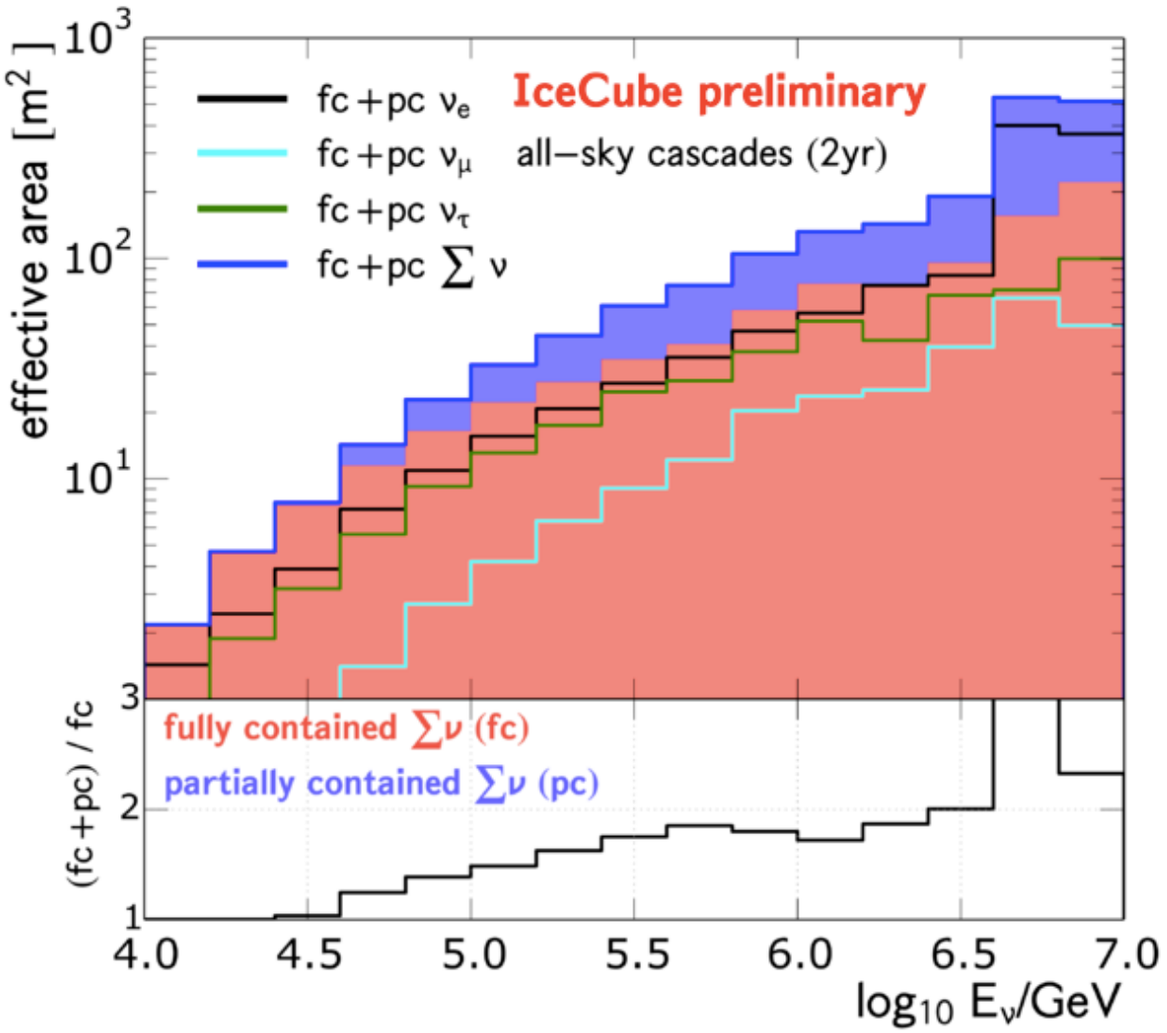
- very low statistics
- very low background

ν_τ

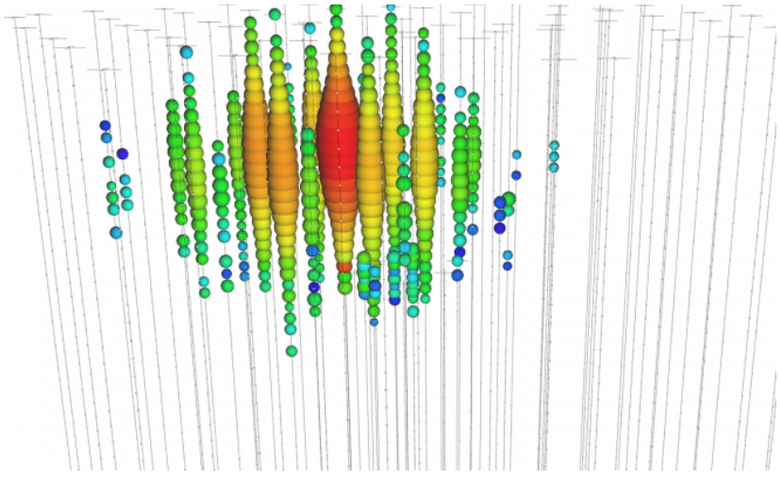


Shower events

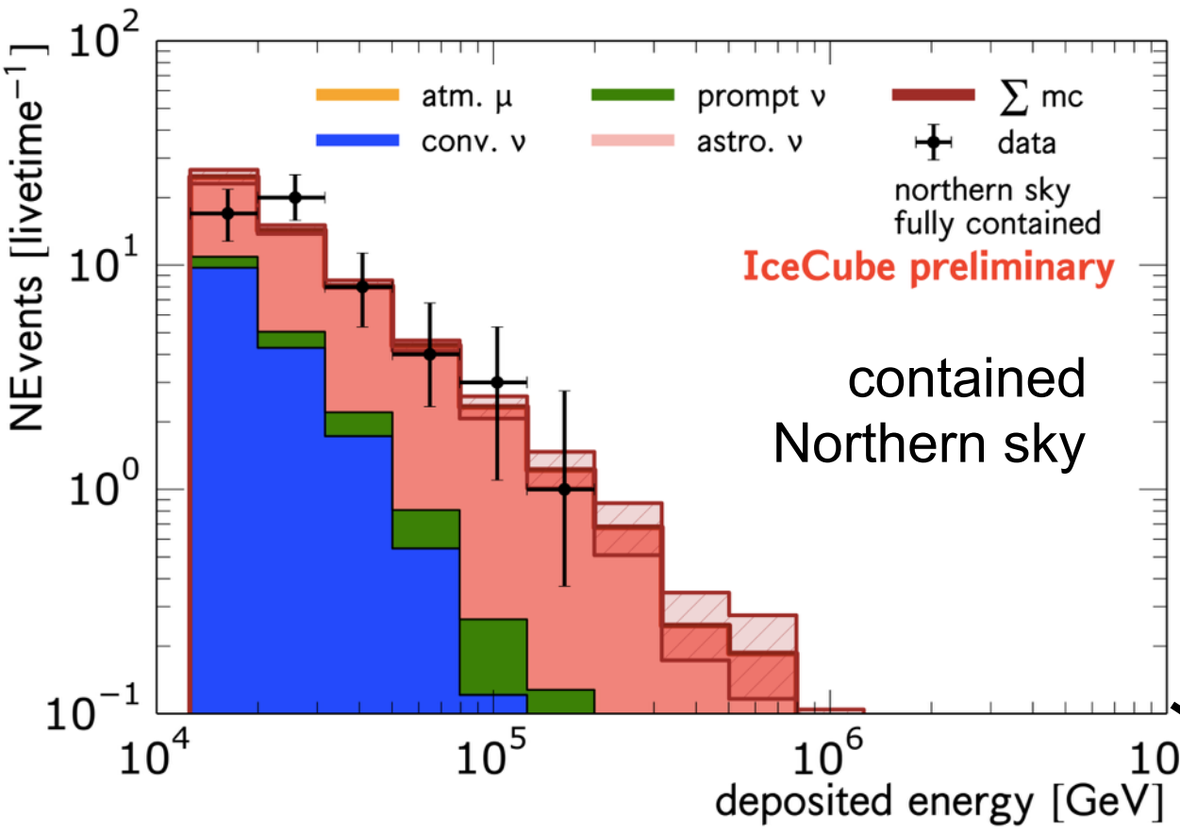


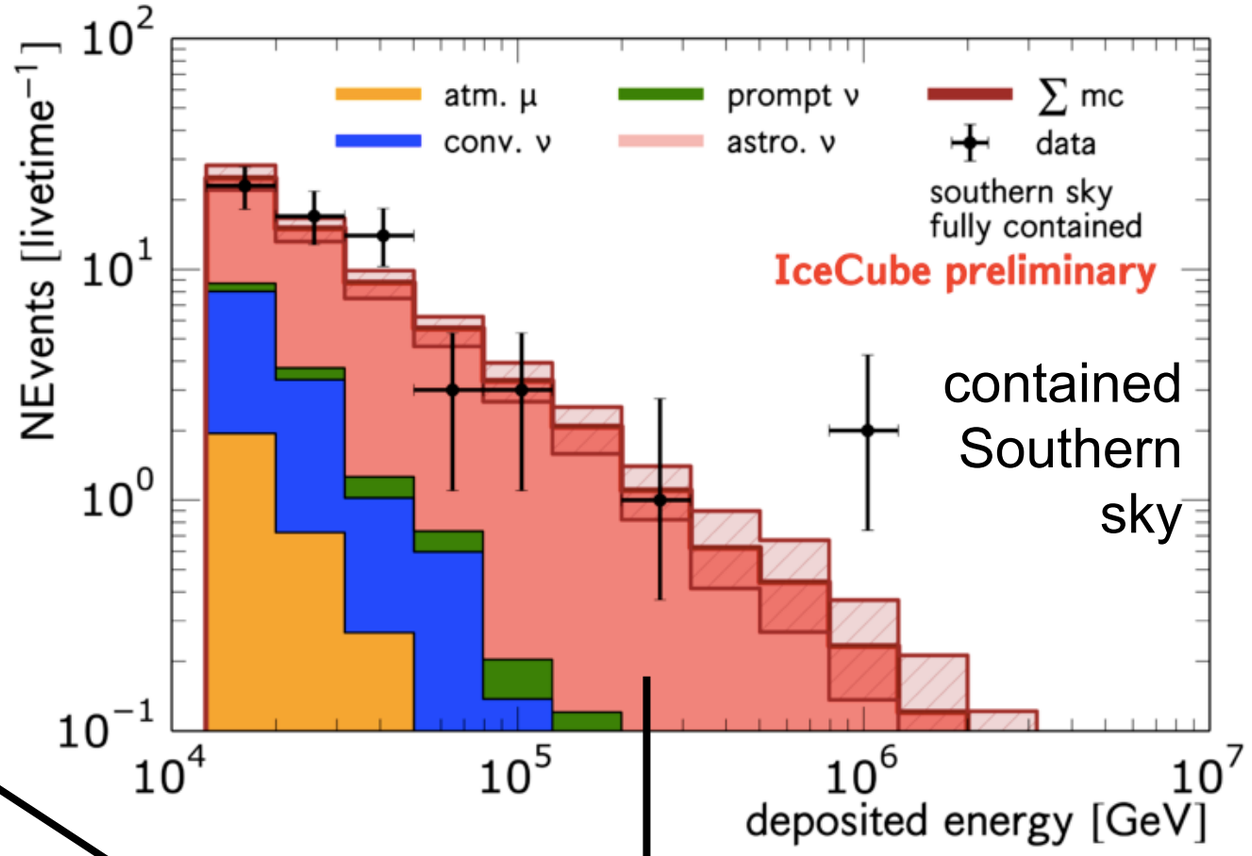


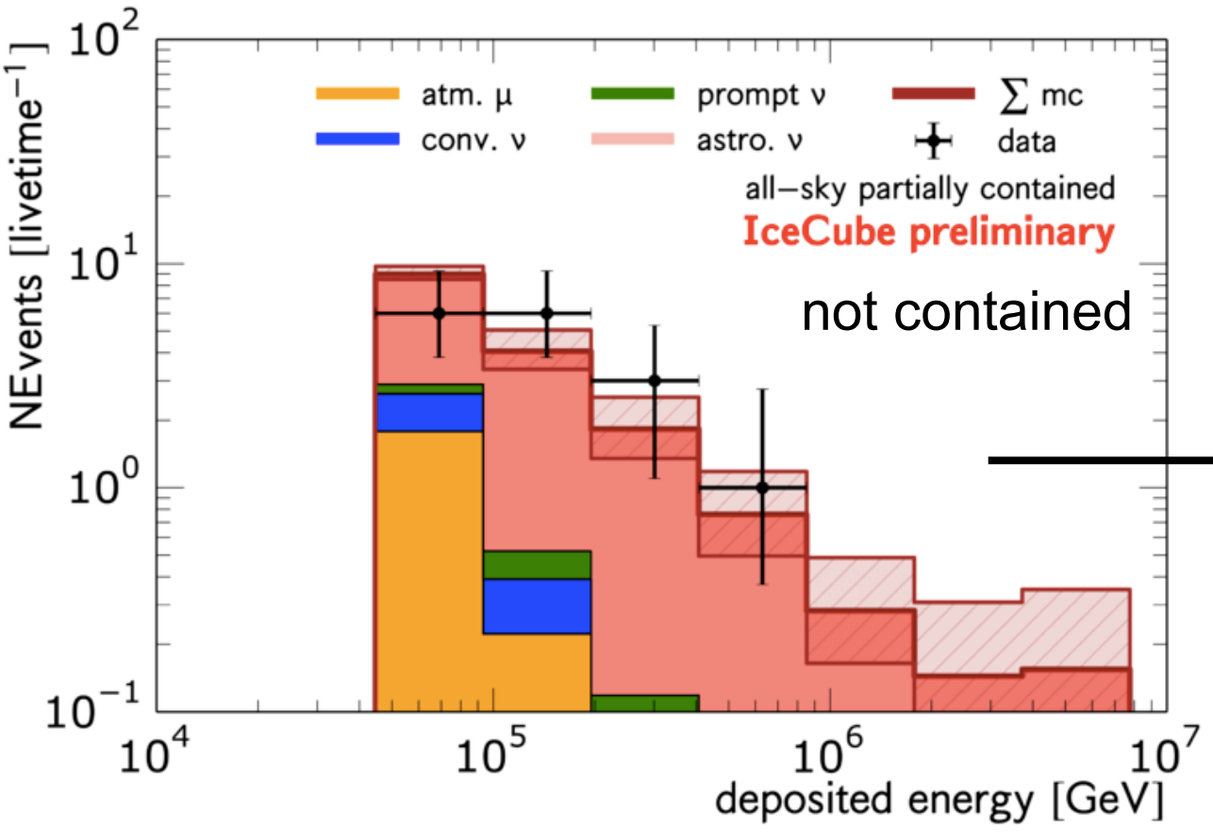
- Showers can be selected based on their **spherical light patterns**
- About **factor of 2 gain** in effective area above 300 TeV
- ~ 60% more events below ~ 100 TeV
- Accurate background simulation required.

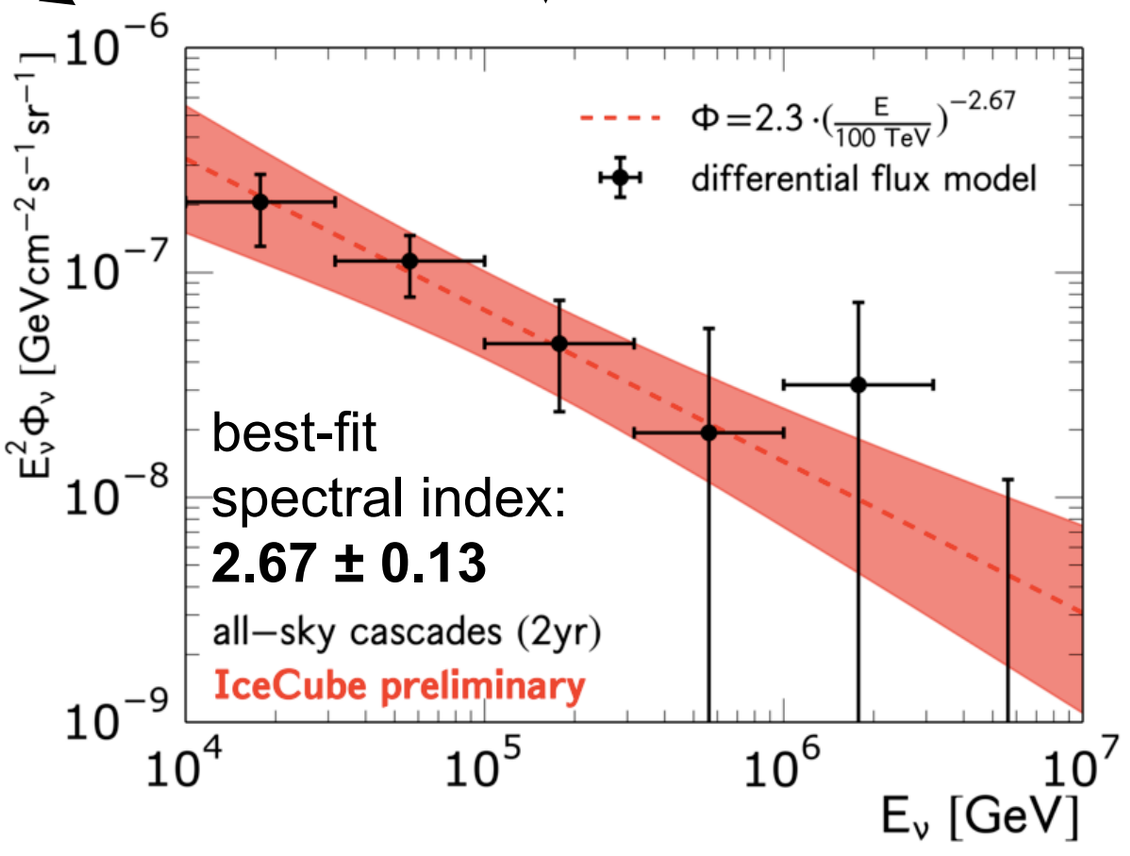


Shower events in two years of IceCube data.

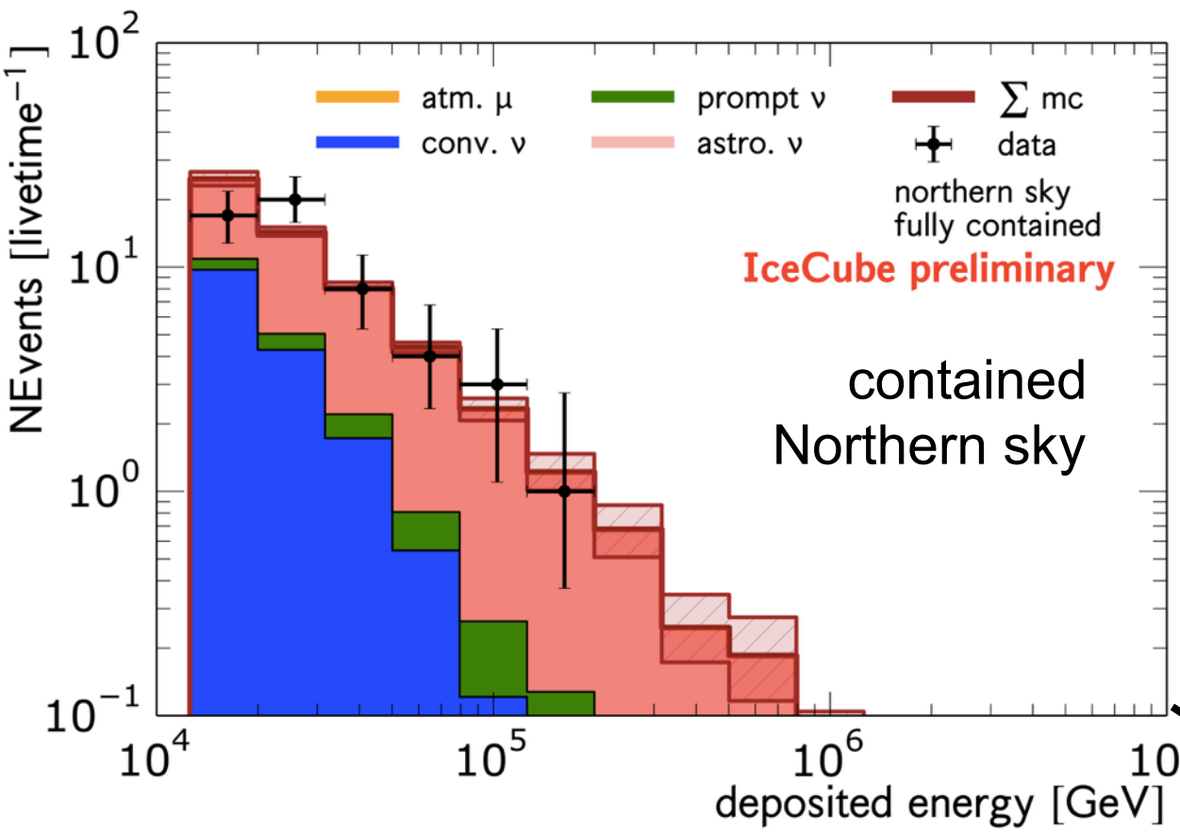


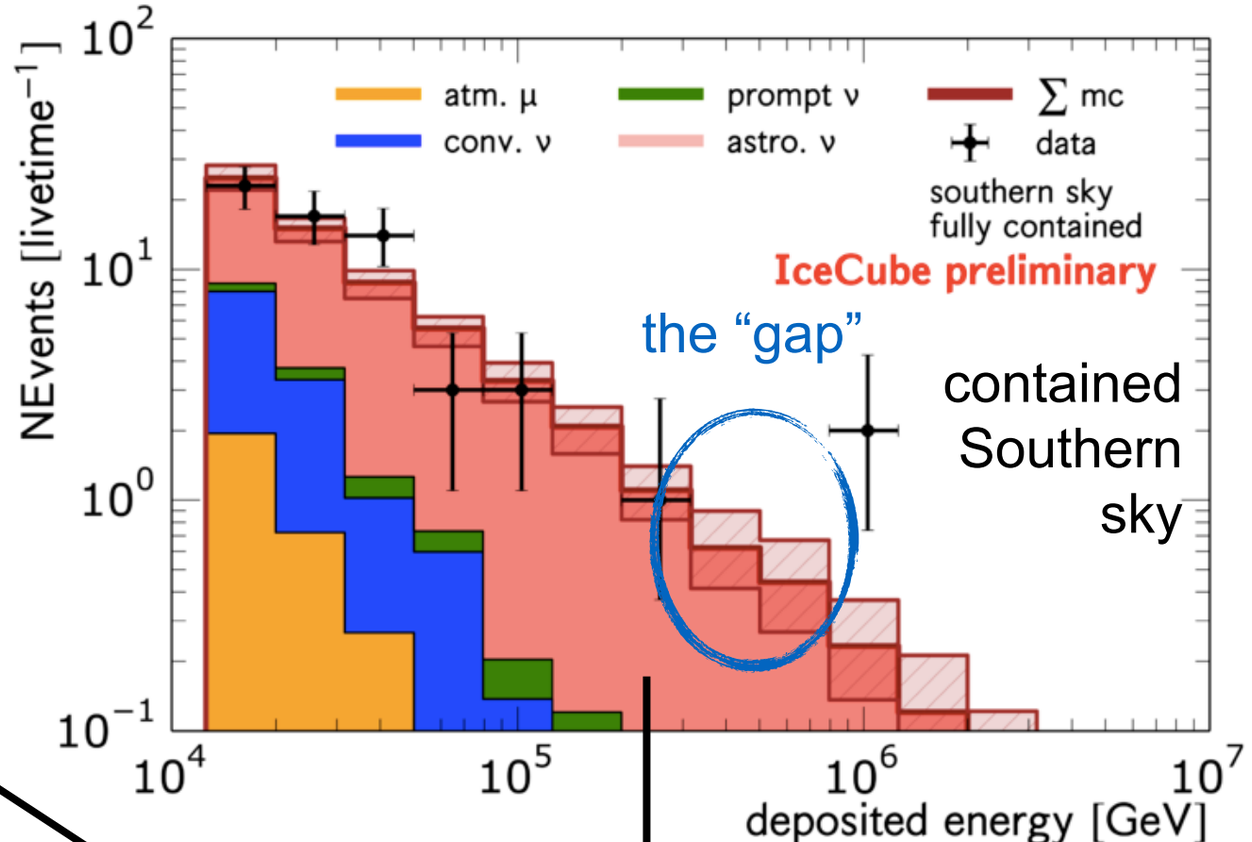


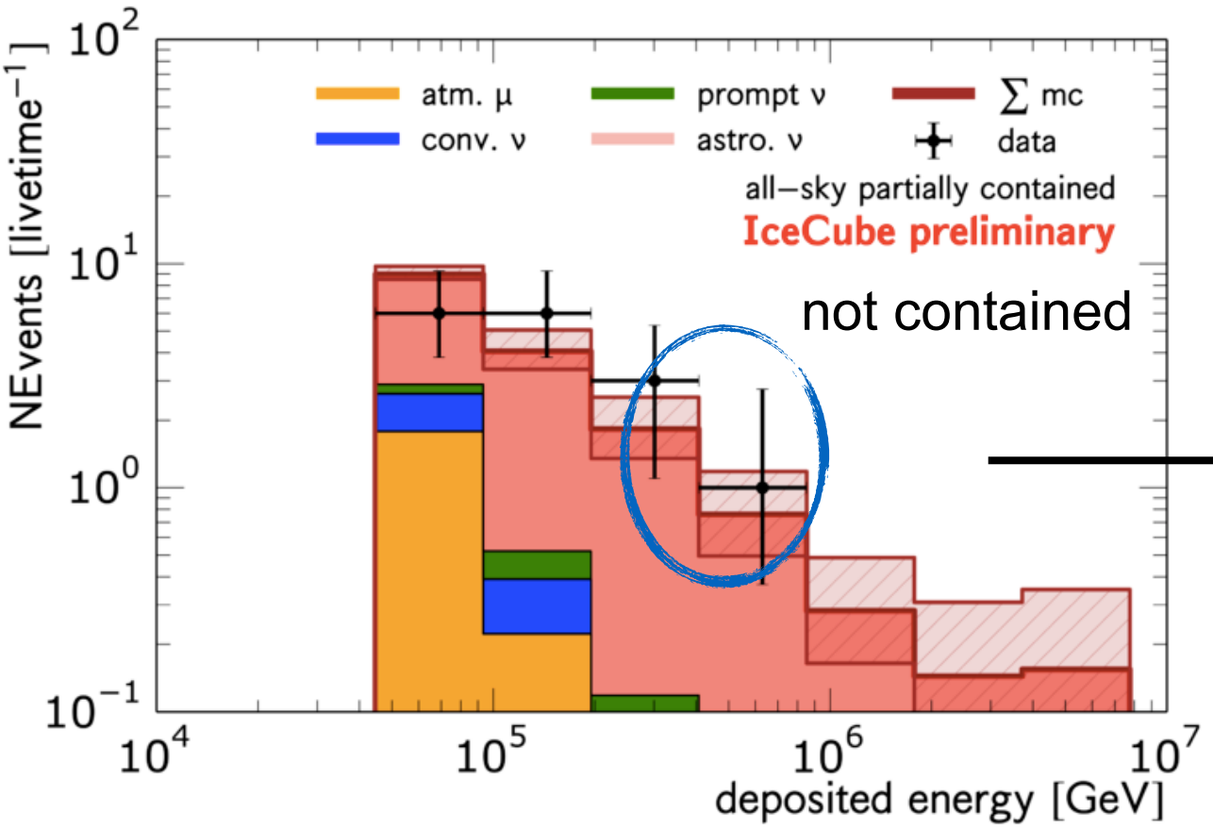


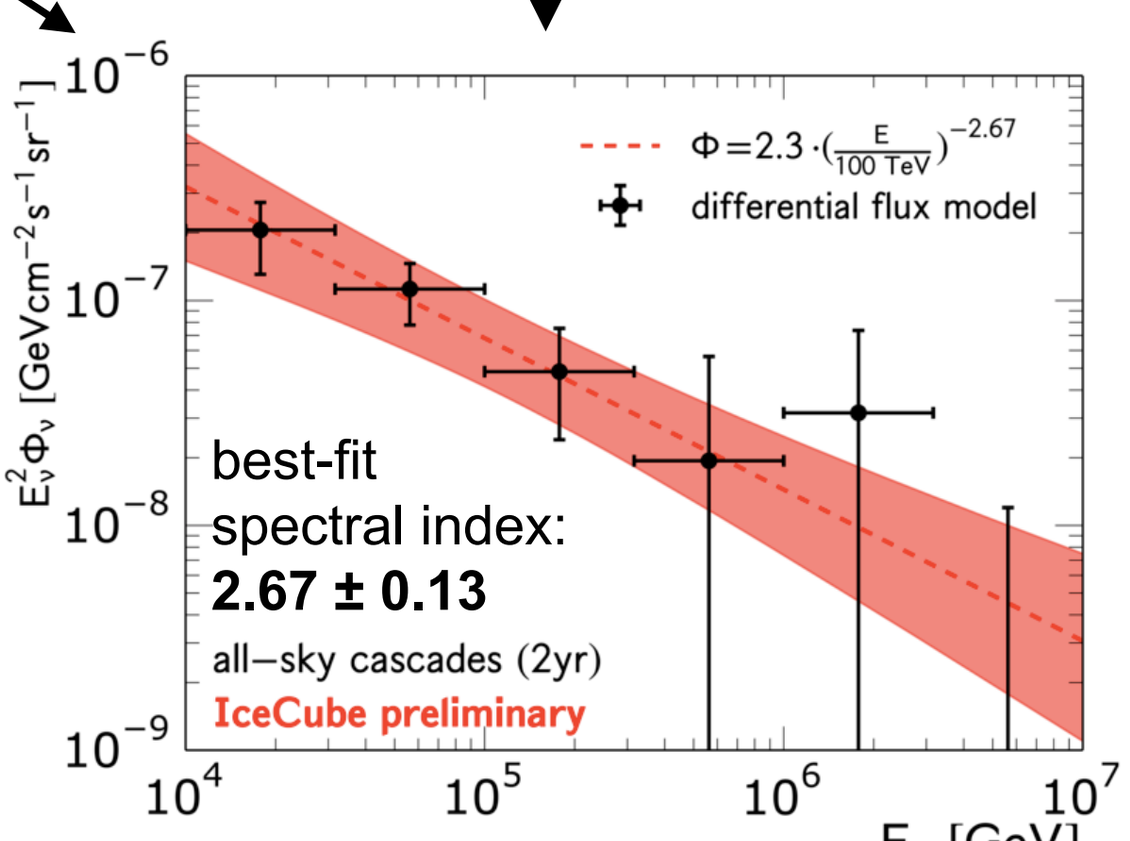


Shower events in two years of IceCube data.









More statistics: Contained / non-contained shower events

ν_μ

tracks

- high statistics
- high background
- good resolution

ν_e, ν_μ, ν_τ

showers

- high statistics
- low background
- bad resolution

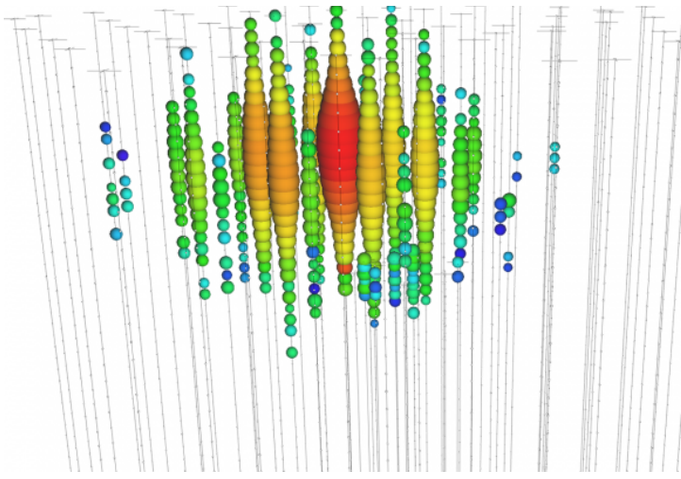
starting events

tau signatures

- very low statistics
- very low background

ν_τ

Confirmation of soft spectrum below 100 TeV
No spectral “gap” at few hundred TeV

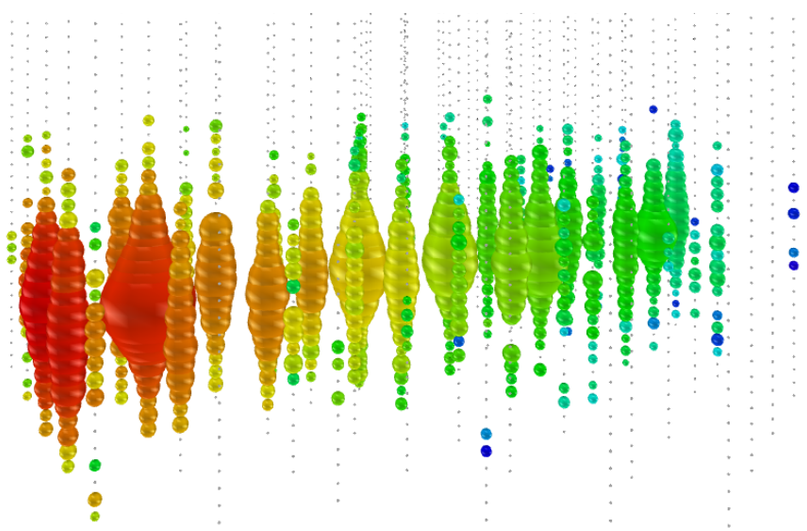


The classic neutrino signature: tracks

ν_μ

tracks

- high statistics
- high background
- good resolution



starting events

ν_e, ν_μ, ν_τ

showers

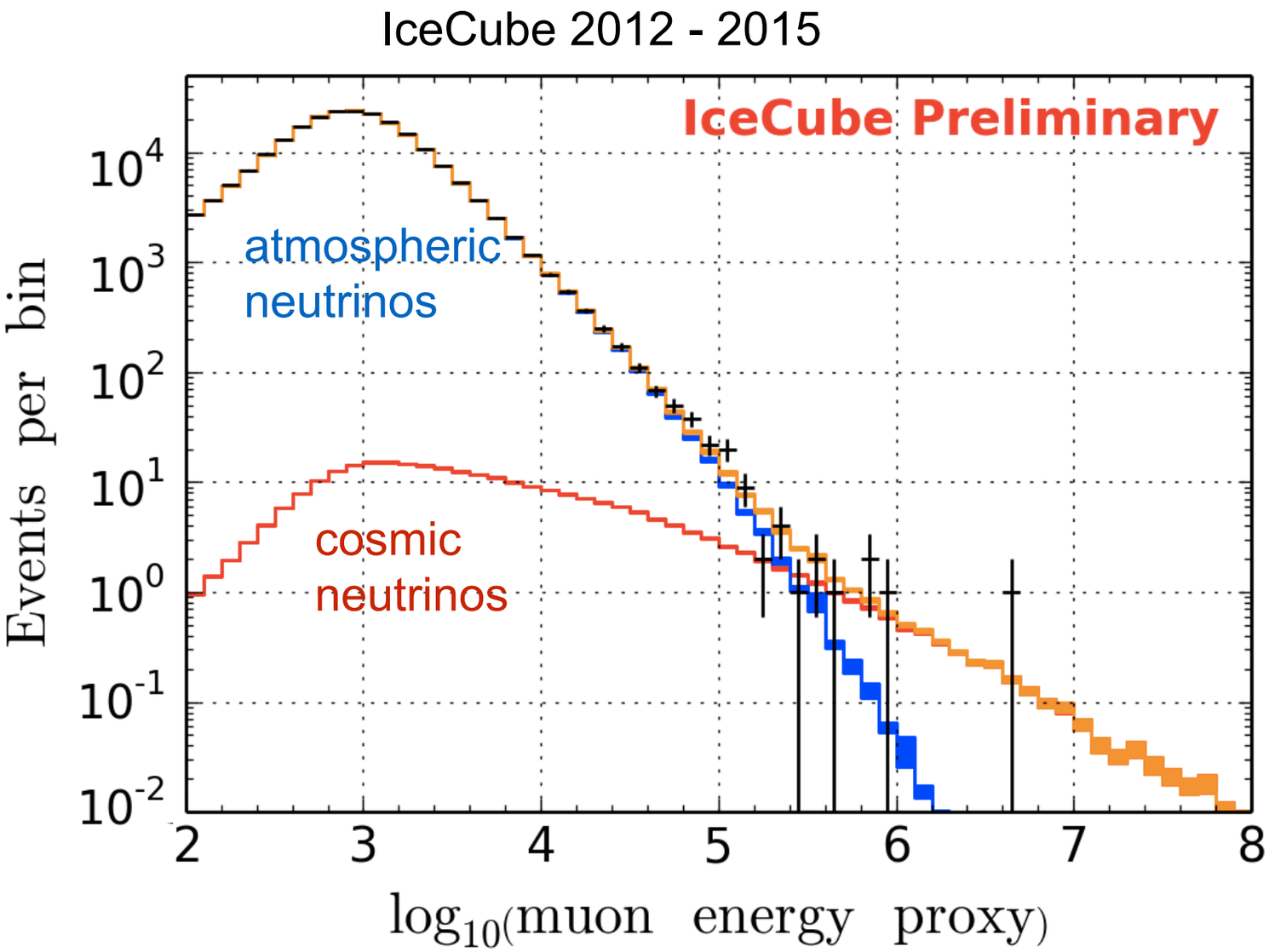
- high statistics
- low background
- bad resolution

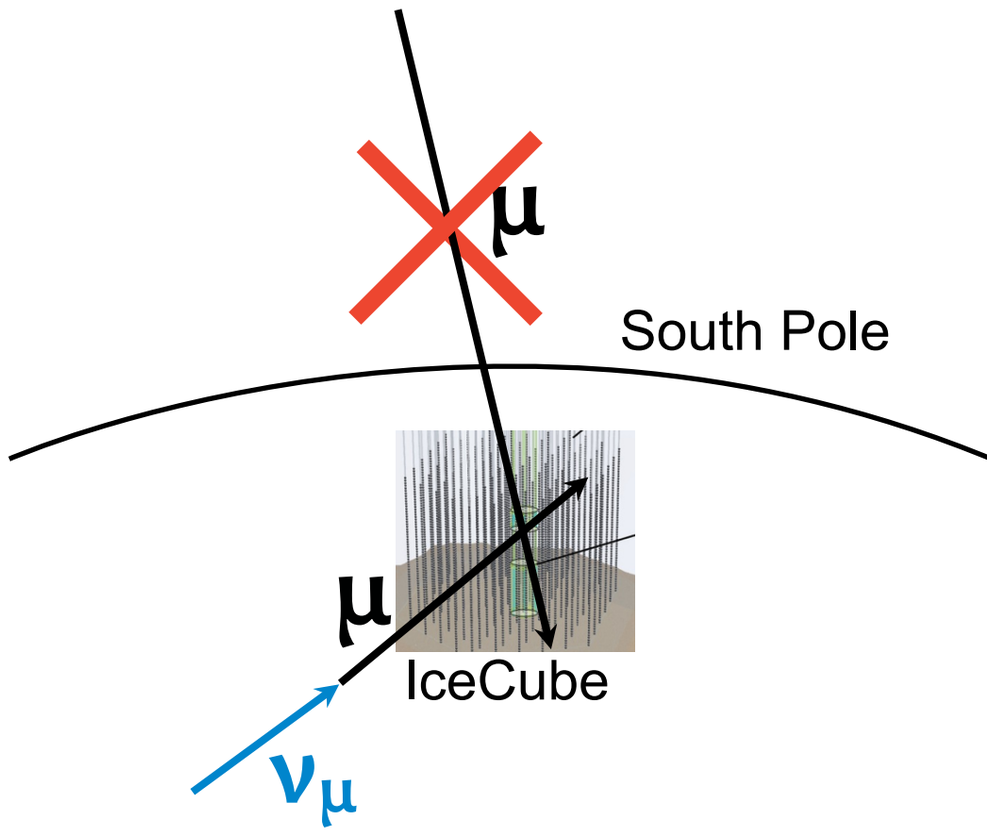
tau signatures

- very low statistics
- very low background

ν_τ

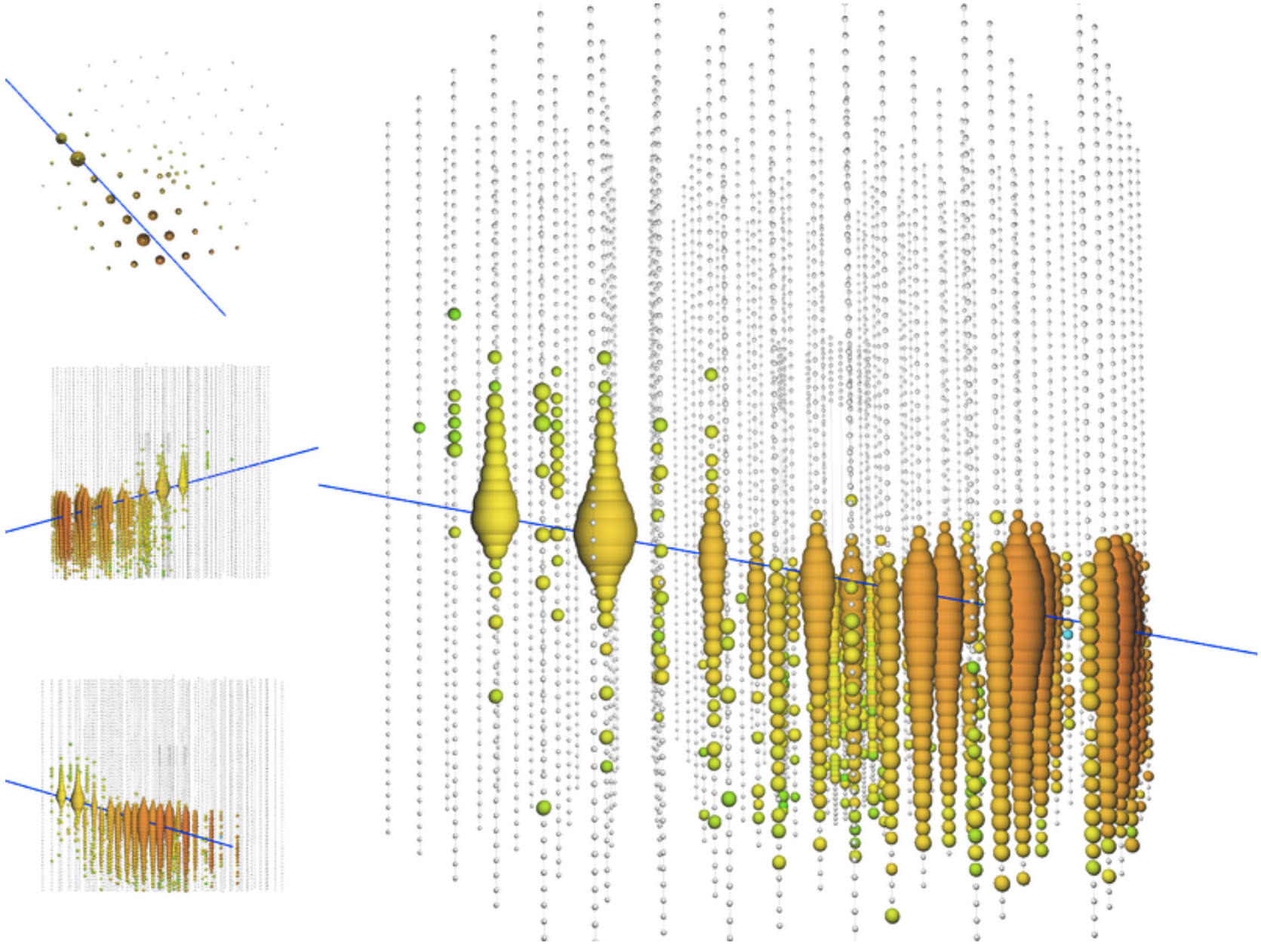
Search for high-energy through-going tracks





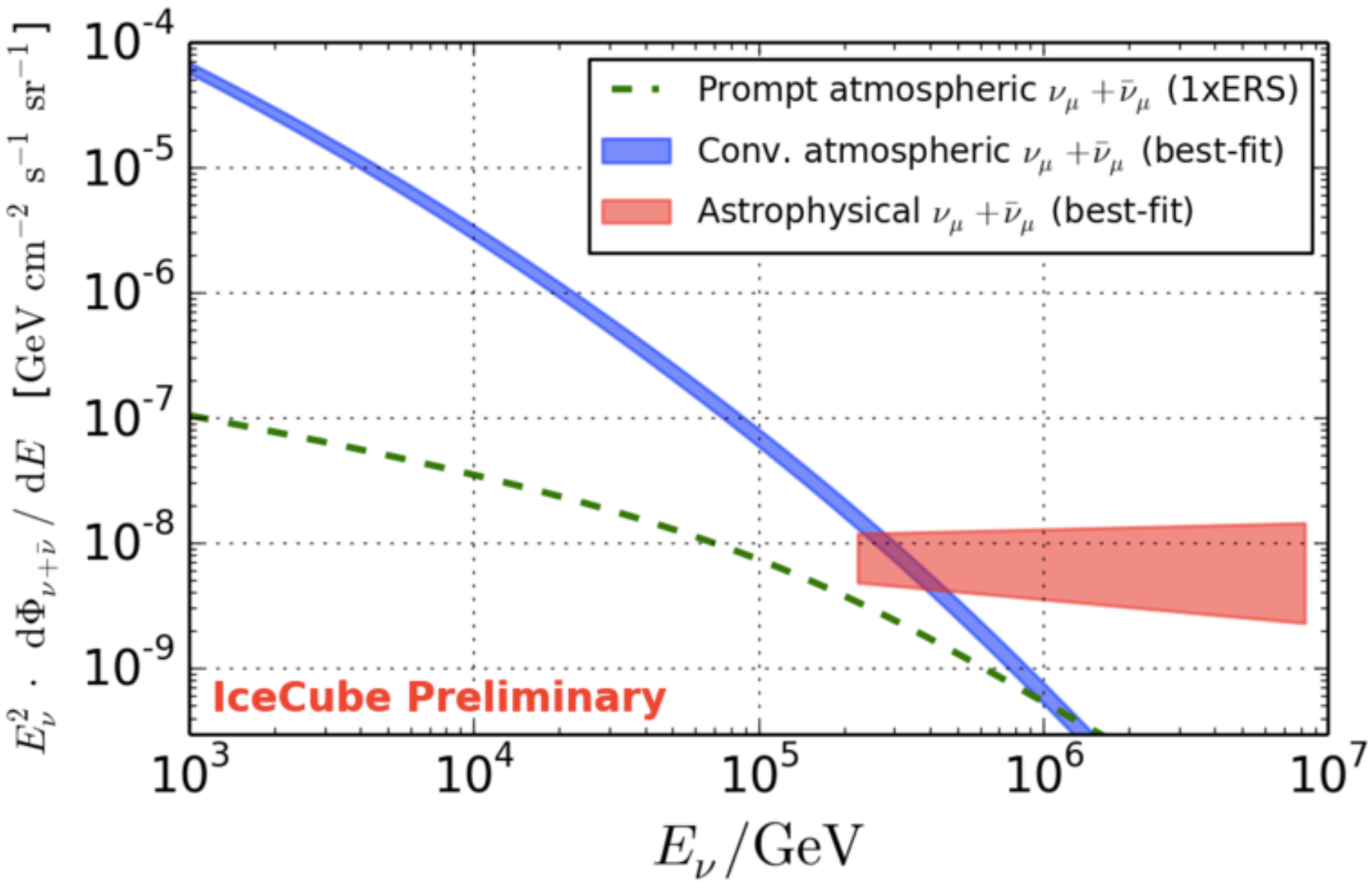
- Search for high-energy excess in 6 years of IceCube muon track data.
- Use low-energy atmospheric neutrino data to fit uncertainties in background.
- **Only Northern hemisphere**!

The highest energy neutrino observed so far….



- **2.6 ± 0.3 PeV** deposited in detector.
- Angular uncertainty: **0.27°**
- Probability for atmospheric origin: **<0.01%**

Spectral fit of through-going track sample.



- A **hard spectrum** is preferred by the muon-track data.
- Best fit spectral index: **2.08 ± 0.13**
- But **energy range is different** than for starting event / shower analyses.

The classic neutrino signature: tracks

ν_μ

tracks

- high statistics
- high background
- good resolution

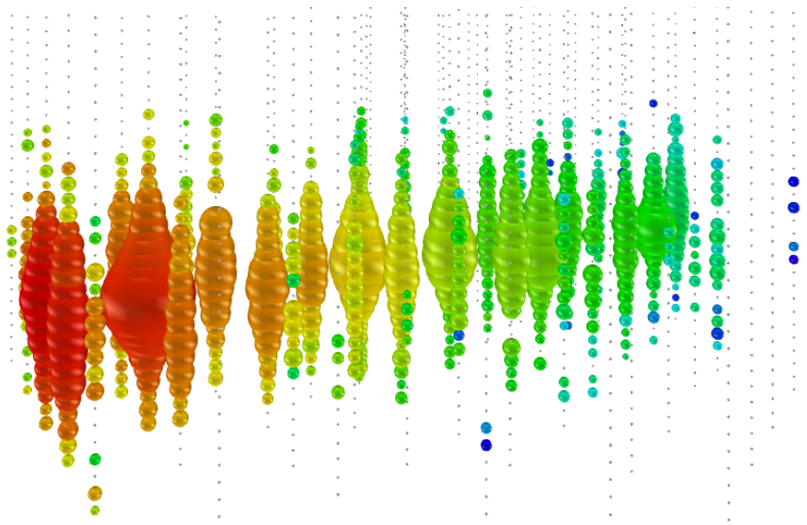
ν_e, ν_μ, ν_τ

showers

- high statistics
- low background
- bad resolution

starting events

Indications of a harder spectrum above few hundred TeV



tau signatures

- very low statistics
- very low background

ν_τ

High energy tau neutrinos

ν_μ

tracks

- high statistics
- high background
- good resolution

ν_e, ν_μ, ν_τ

showers

- high statistics
- low background
- bad resolution

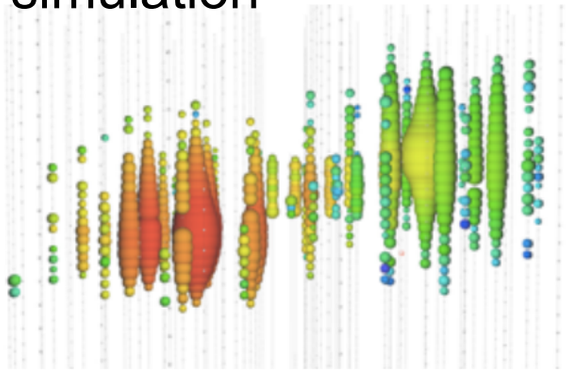
starting events

tau signatures

- very low statistics
- very low background

ν_τ

simulation



Search for tau neutrino signatures

Data samples	Events in 914.1 days (final cut)
Astrophysical ν_τ CC	$(5.4 \pm 0.1) \cdot 10^{-1}$
Astrophysical ν_μ CC	$(1.8 \pm 0.1) \cdot 10^{-1}$
Astrophysical ν_e	$(6.0 \pm 1.7) \cdot 10^{-2}$
Atmospheric ν	$(3.2 \pm 1.4) \cdot 10^{-2}$
Atmospheric muons	$(7.5 \pm 5.8) \cdot 10^{-2}$

Aartsen et al., submitted to PRD.

- 3 years of IceCube data analyzed
- **0.54** cosmic tau neutrinos **expected**, **none observed**

High energy tau neutrinos

ν_μ

tracks

- high statistics
- high background
- good resolution

ν_e, ν_μ, ν_τ

showers

- high statistics
- low background
- bad resolution

starting events

Non-observation compatible with expectations
Need more data !

tau signatures

- very low statistics
- very low background

ν_τ

The global fit.

ν_μ

tracks

- high statistics
- high background
- good resolution

ν_e, ν_μ, ν_τ

showers

- high statistics
- low background
- bad resolution

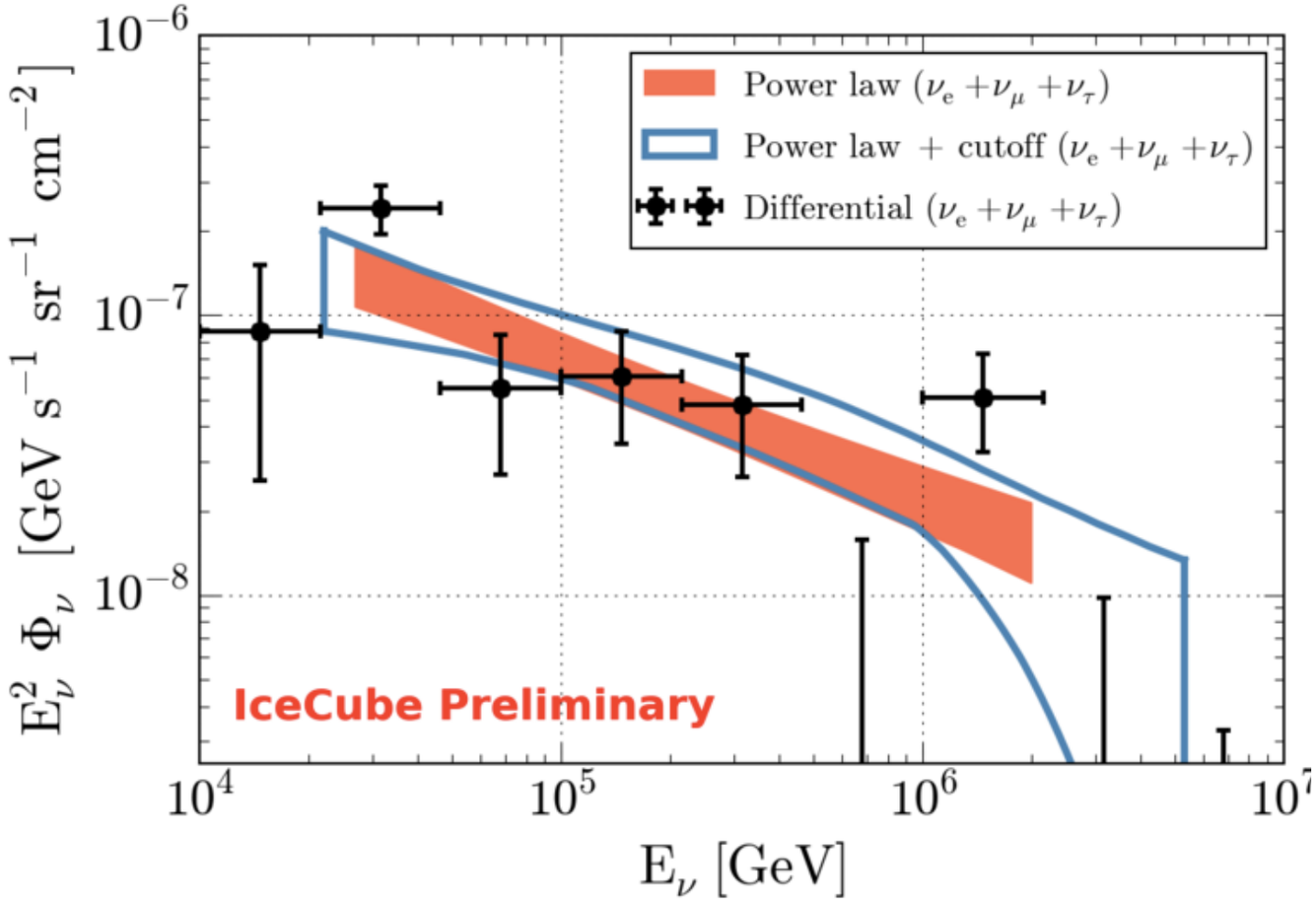
starting events

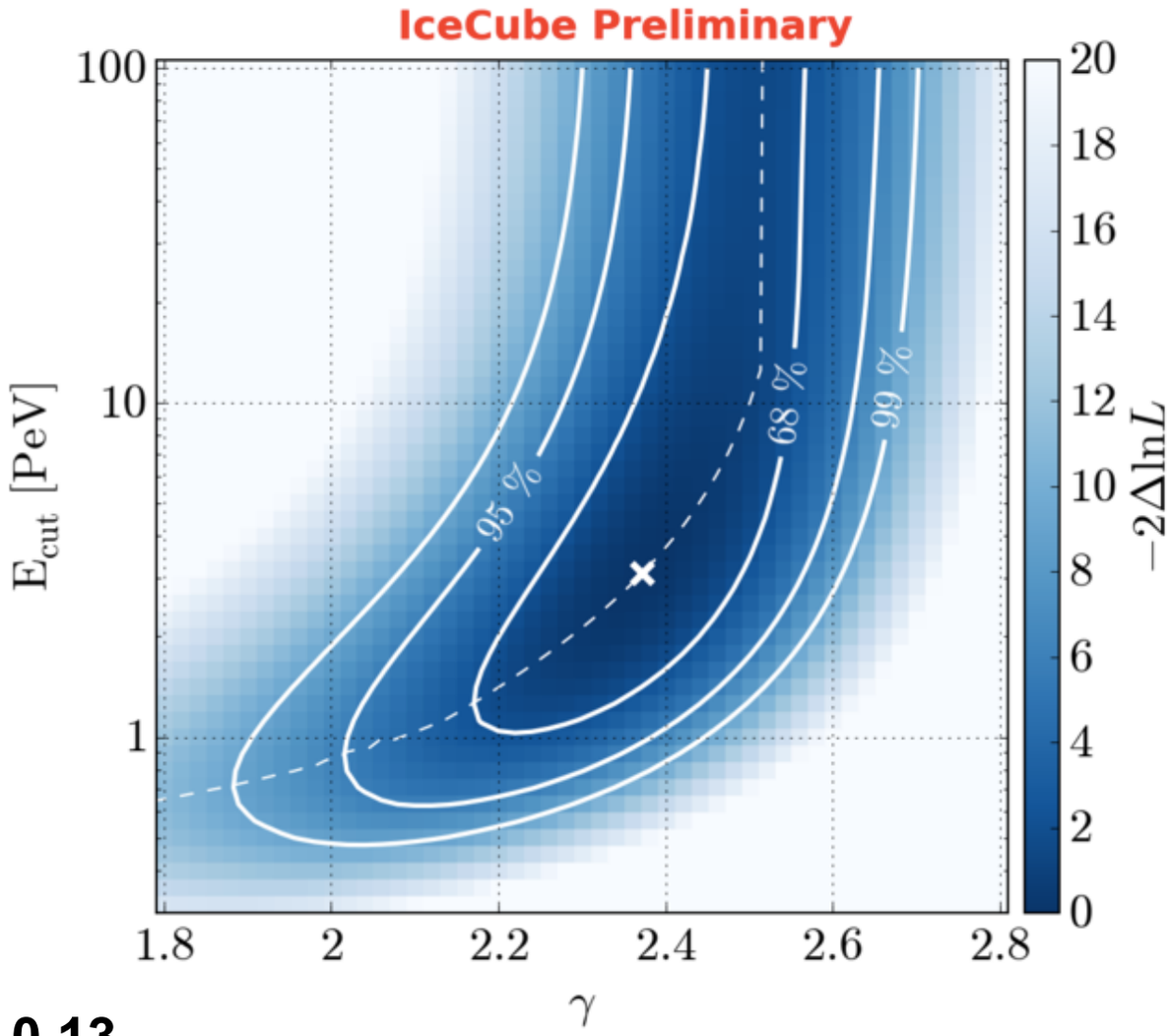
tau signatures

- very low statistics
- very low background

ν_τ

Best fit astrophysical neutrino spectrum using all channels

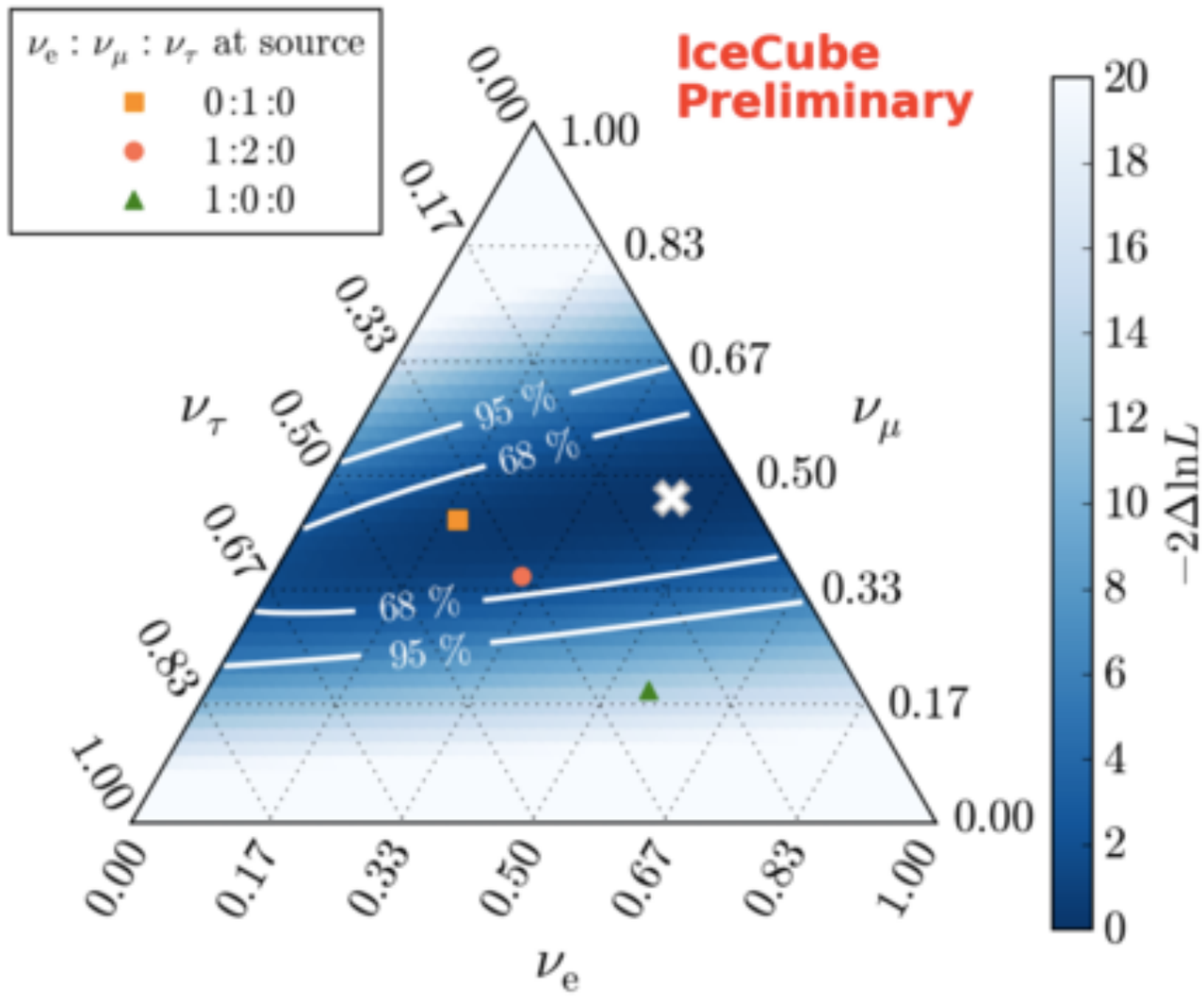




spectral index: **2.52 ± 0.07** or spectral index: **2.37 ± 0.13**
cutoff energy: **3.1 PeV**

- **Combines** starting event, shower, track and tau **channels**.
- Does only contain **3 years of through-going track** data !
- Simple power law spectrum and power law + cutoff both compatible with IceCube data.

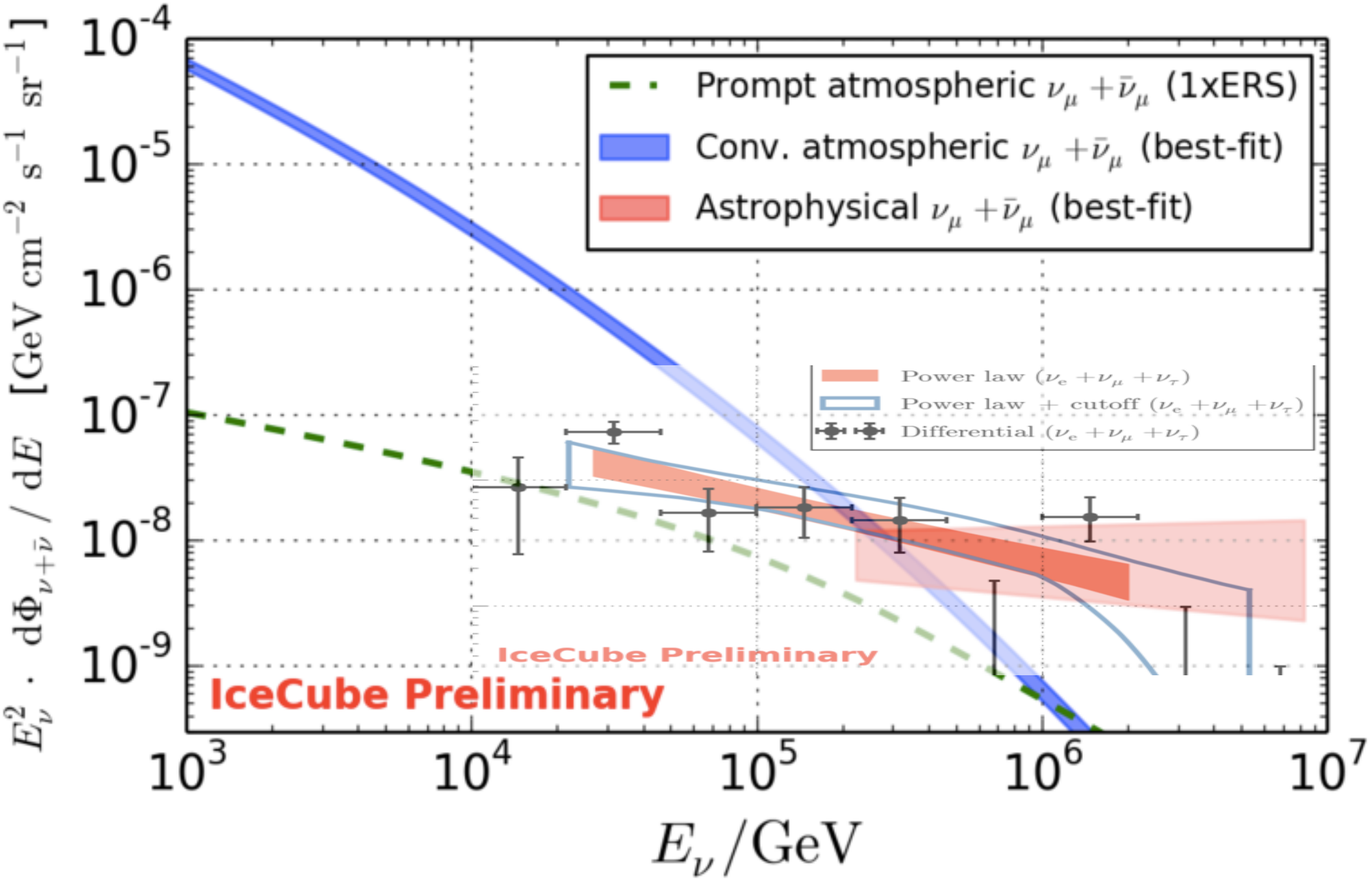
Neutrino flavor ratio constraints.



> Flavor ratios **compatible with standard pion decay production** (1:2:0) and **muon damped scenarios** (0:1:0)

> **Beta decay origin** (1:0:0) can be excluded at 3σ level.

Do we get a consistent picture ?



- **No real tension** due to different energy ranges.
- Some **indications for spectral hardening** at high energies.
- Significance still needs to be quantified.

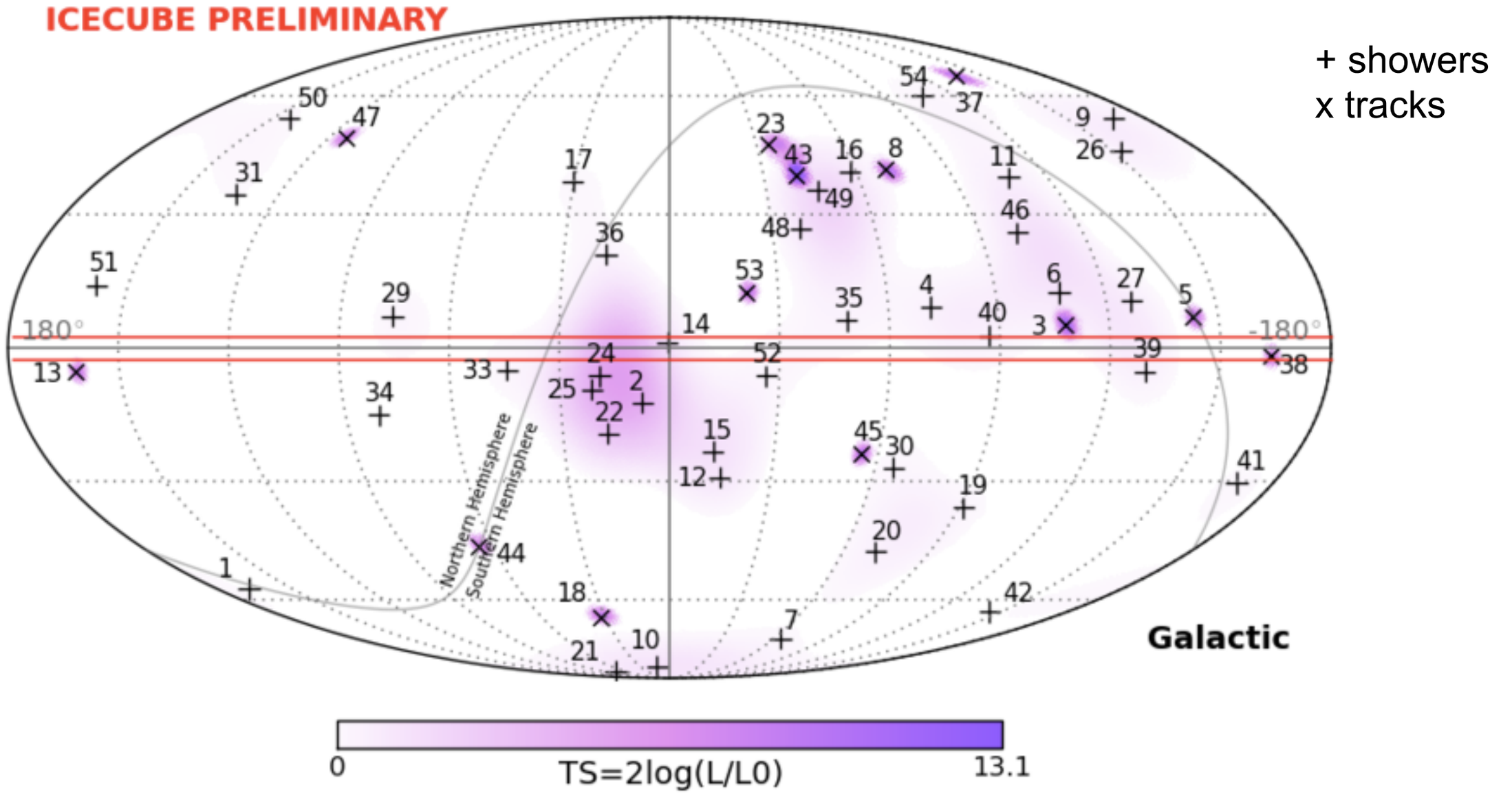
Where are the cosmic neutrinos from ?

Is it a single neutrino source / a few sources ?

Single source / few sources scenario.

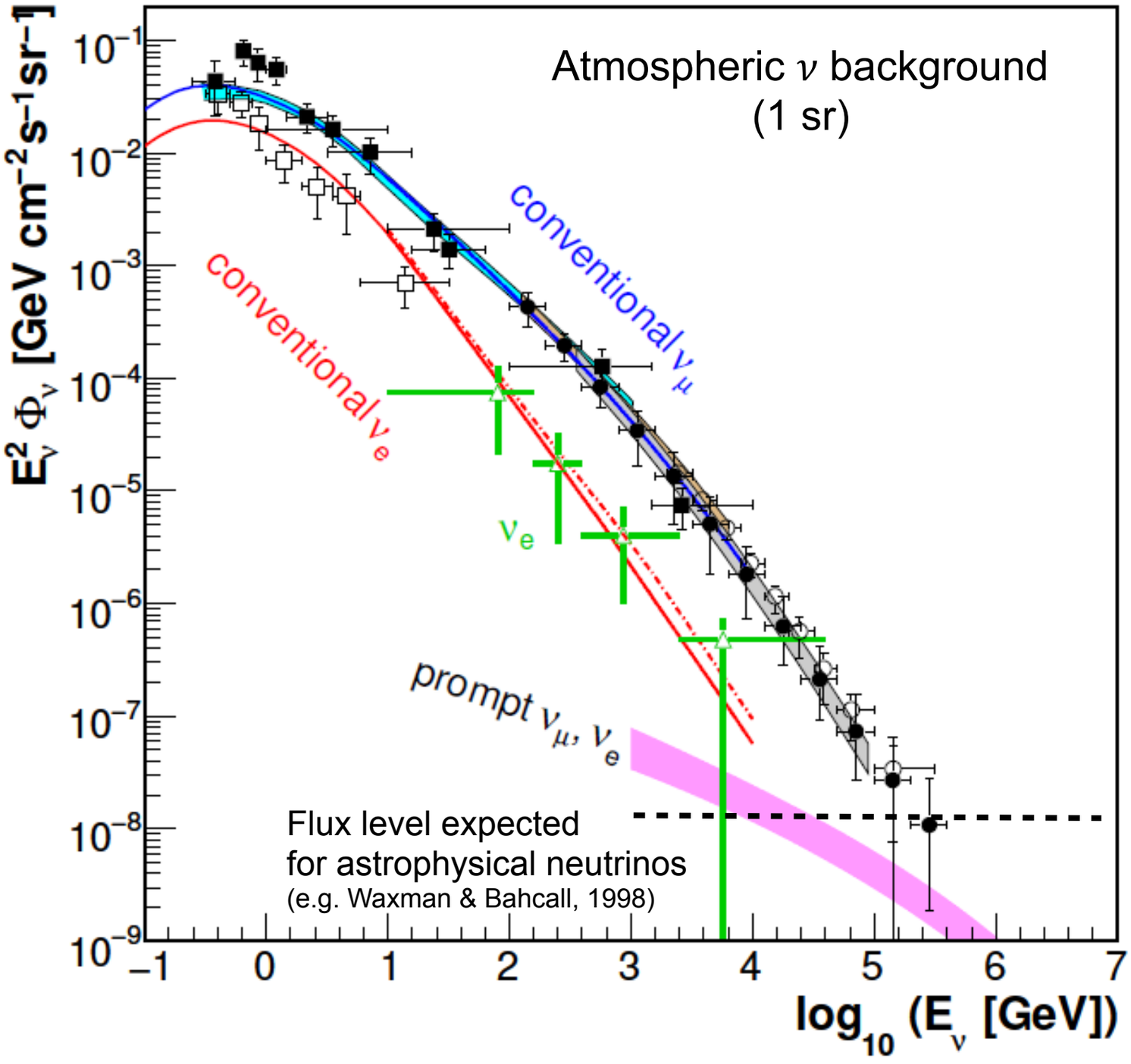
> This event distribution is not compatible with a single source !

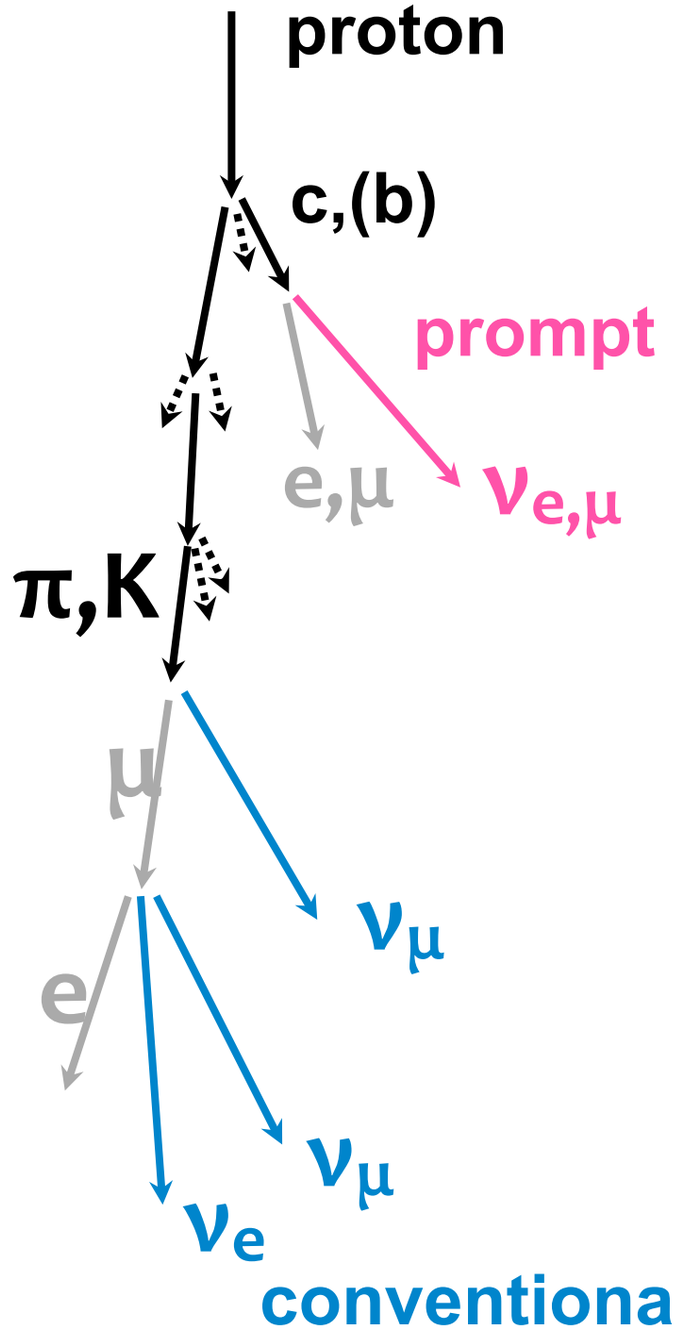
> But we can do better than this…..



Atmospheric backgrounds revisited…..

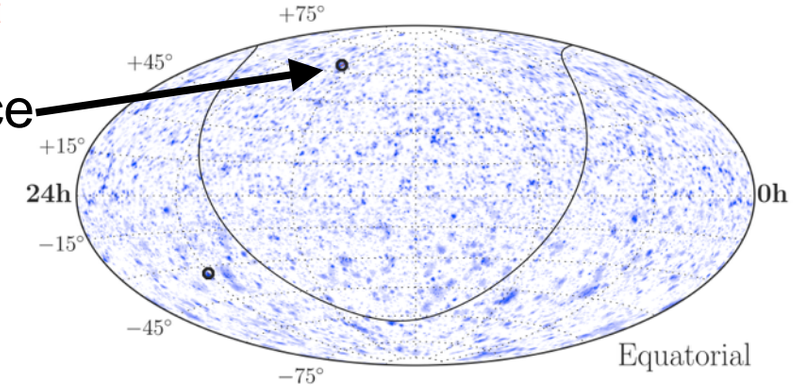
- **Most neutrinos** seen by neutrino telescopes are of **atmospheric origin**.
- Angular resolution for ν_μ better than 1 deg.





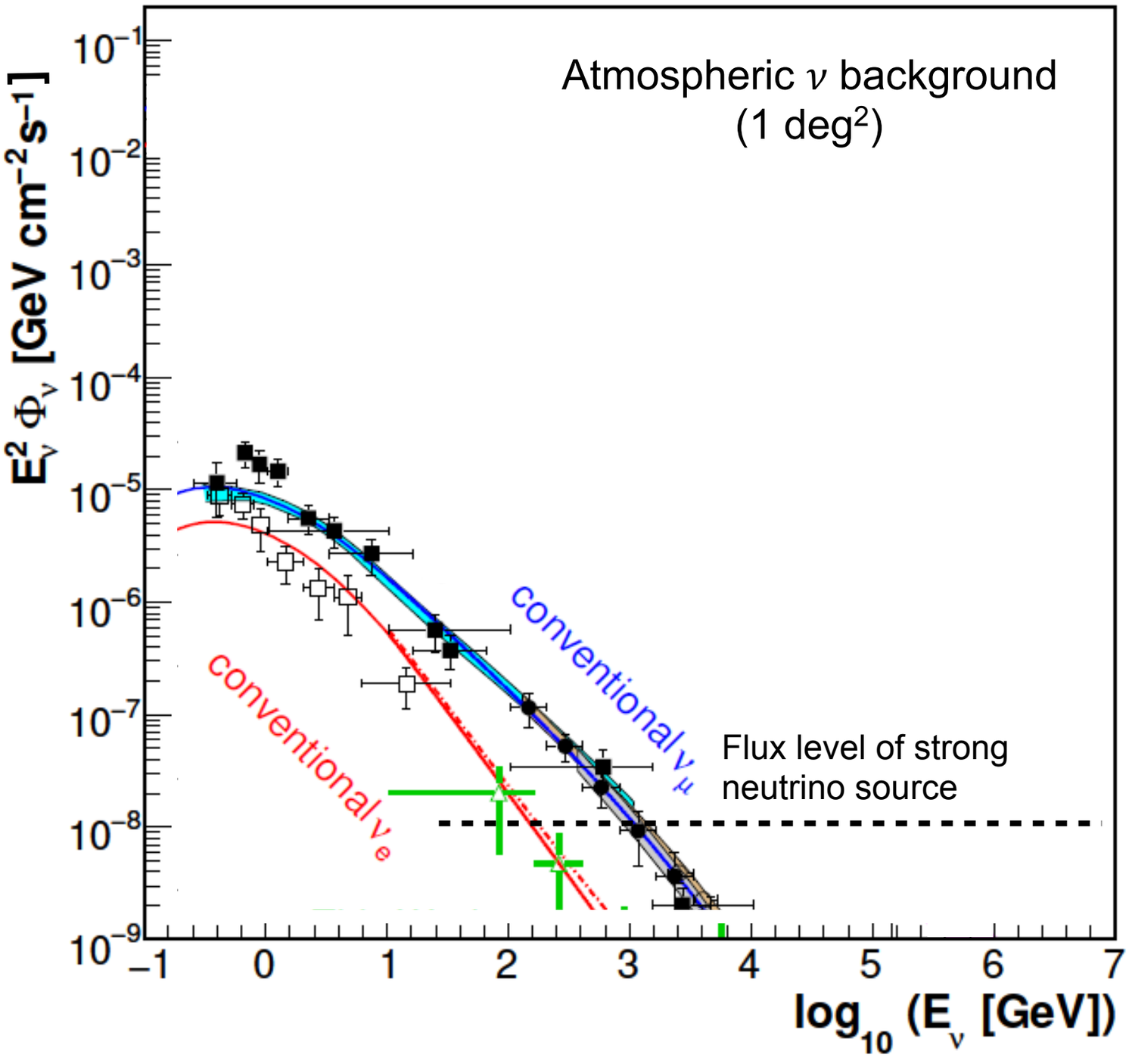
Atmospheric backgrounds for individual source searches

(Potential) neutrino source



Atmospheric neutrinos

> Angular resolution for ν_μ better than 1 deg.



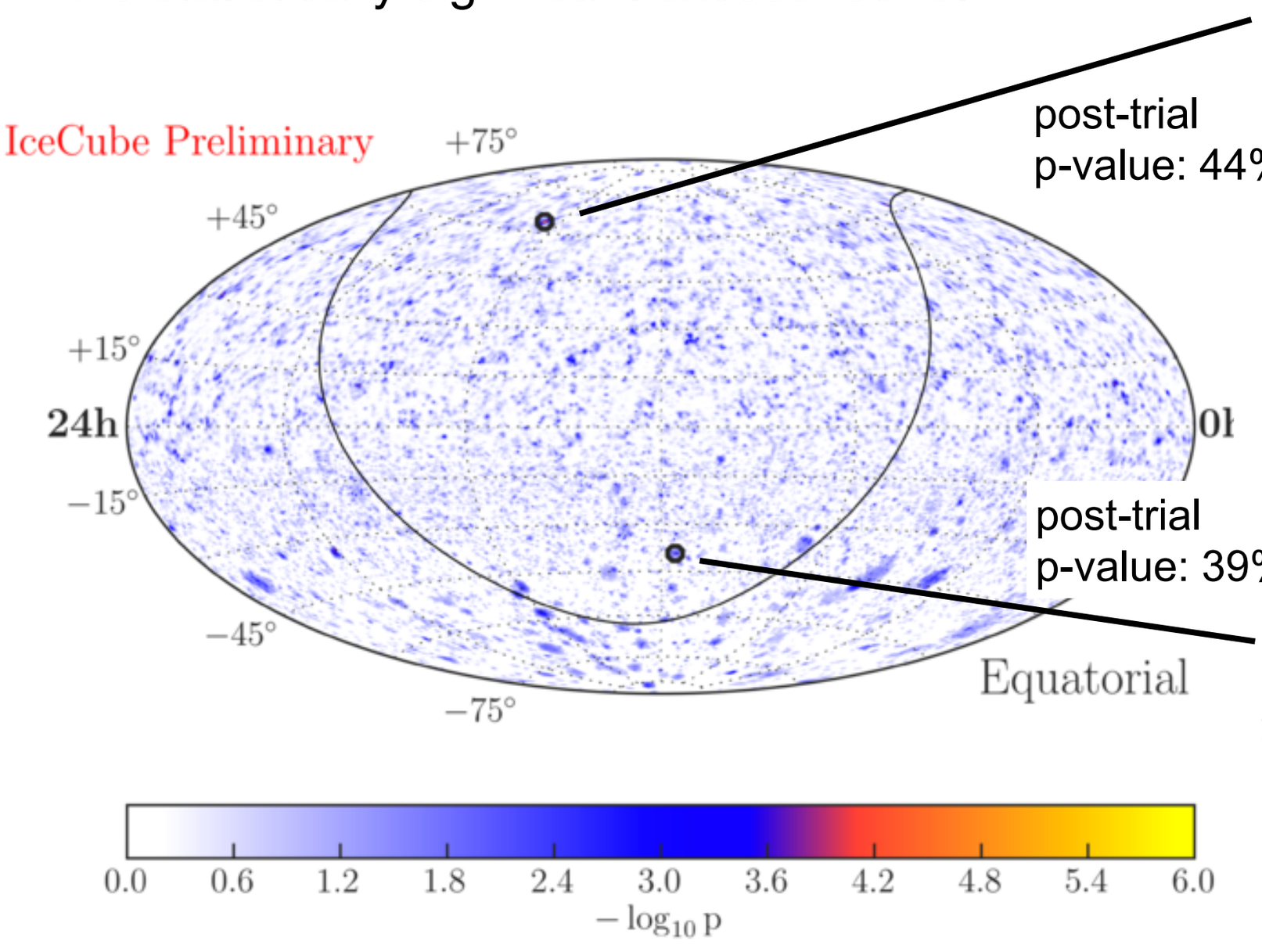
> Atmospheric background is reduced dramatically, if one looks for **individual neutrino sources**

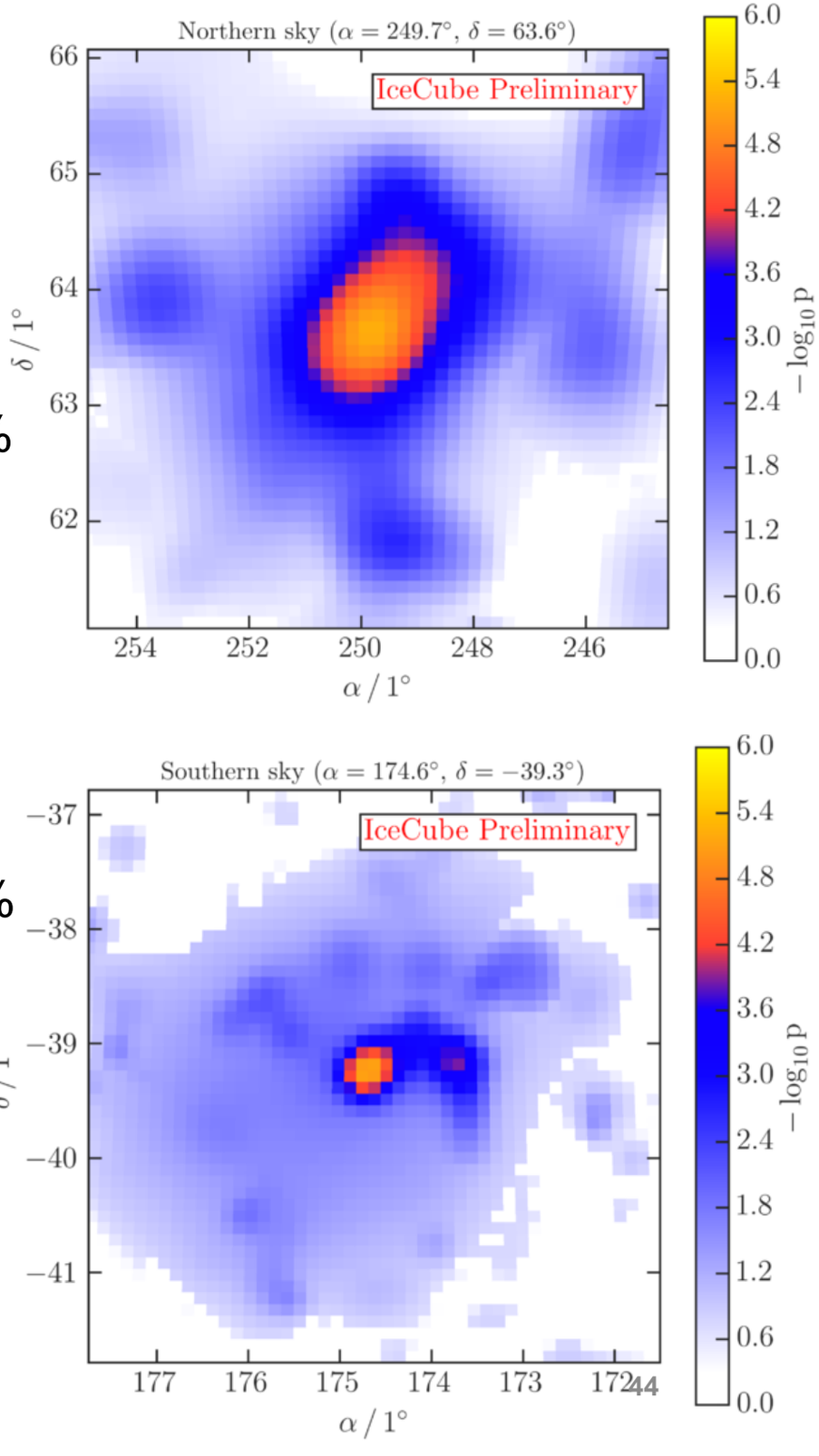
> **Energy threshold** for individual source observation is lower than for a diffuse signal.

> **Sensitivity** is better.

Search for individual neutrino sources: IceCube

- 7 **years** of IceCube data (construction phase + full array)
- Sample of more than **700k muon track events**
- Median **angular resolution:** ~0.5 deg @ 10 TeV
- No statistically significant excess found.





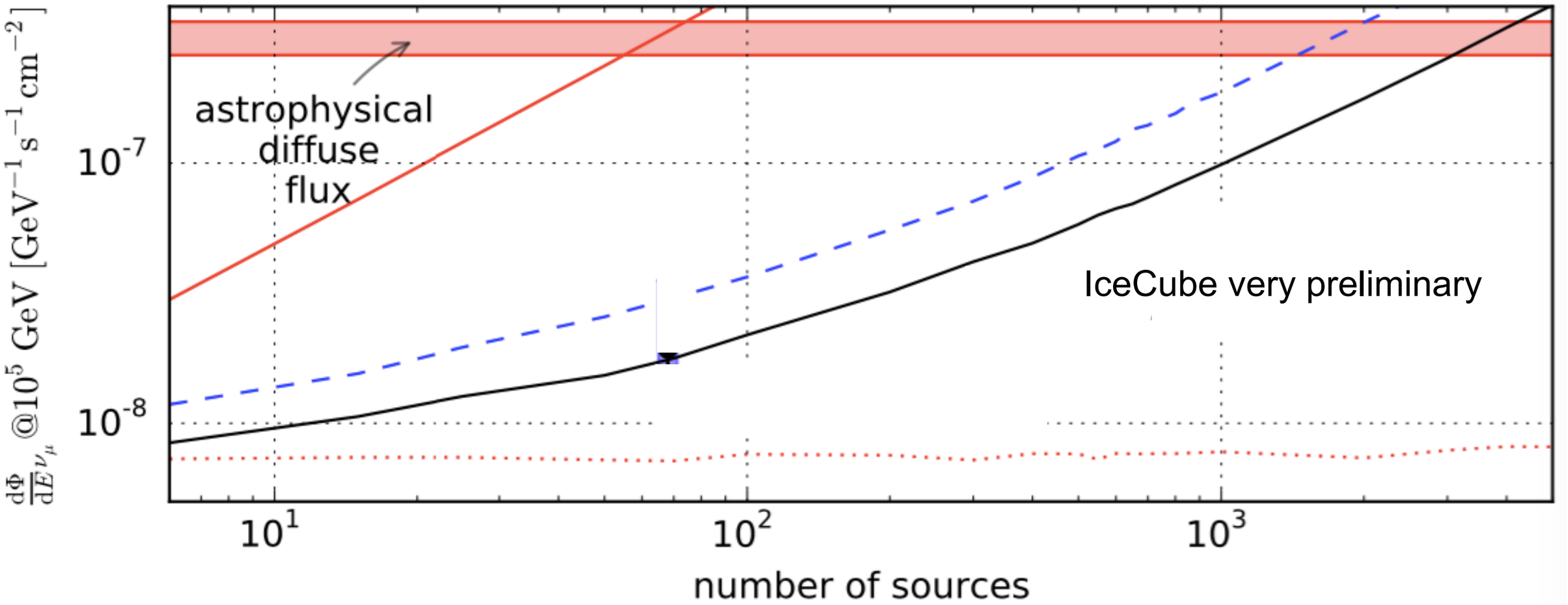
How many sources do we need ?

90% CL lower limits on number of neutrino sources.

Equal flux from all sources

Constant Density/ Luminosity

Source density like gamma-ray Blazars

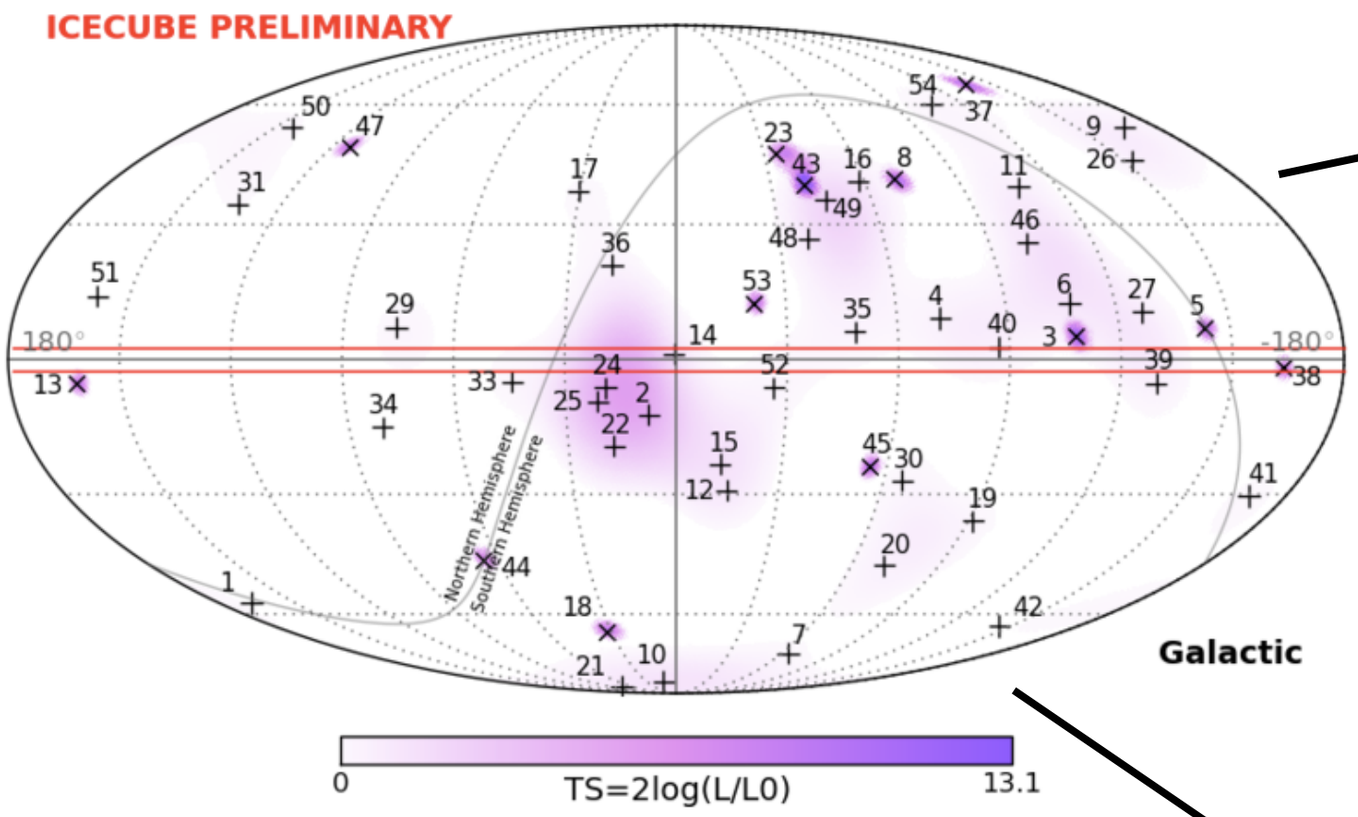


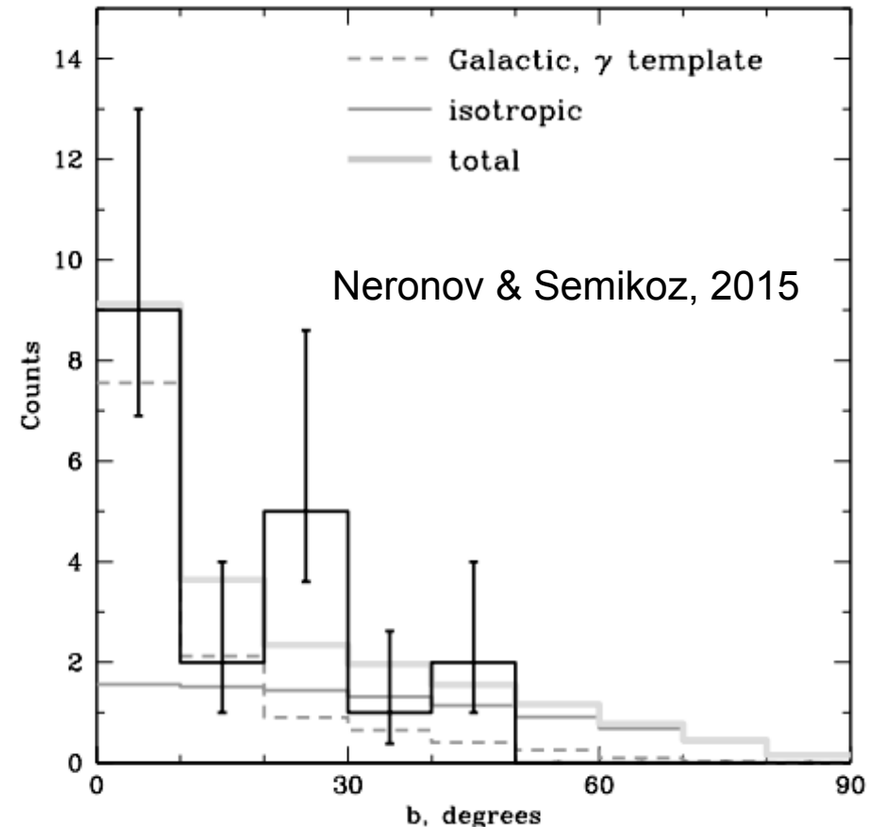
> More than O(10^3) sources need to be responsible for the bulk of the neutrino flux.

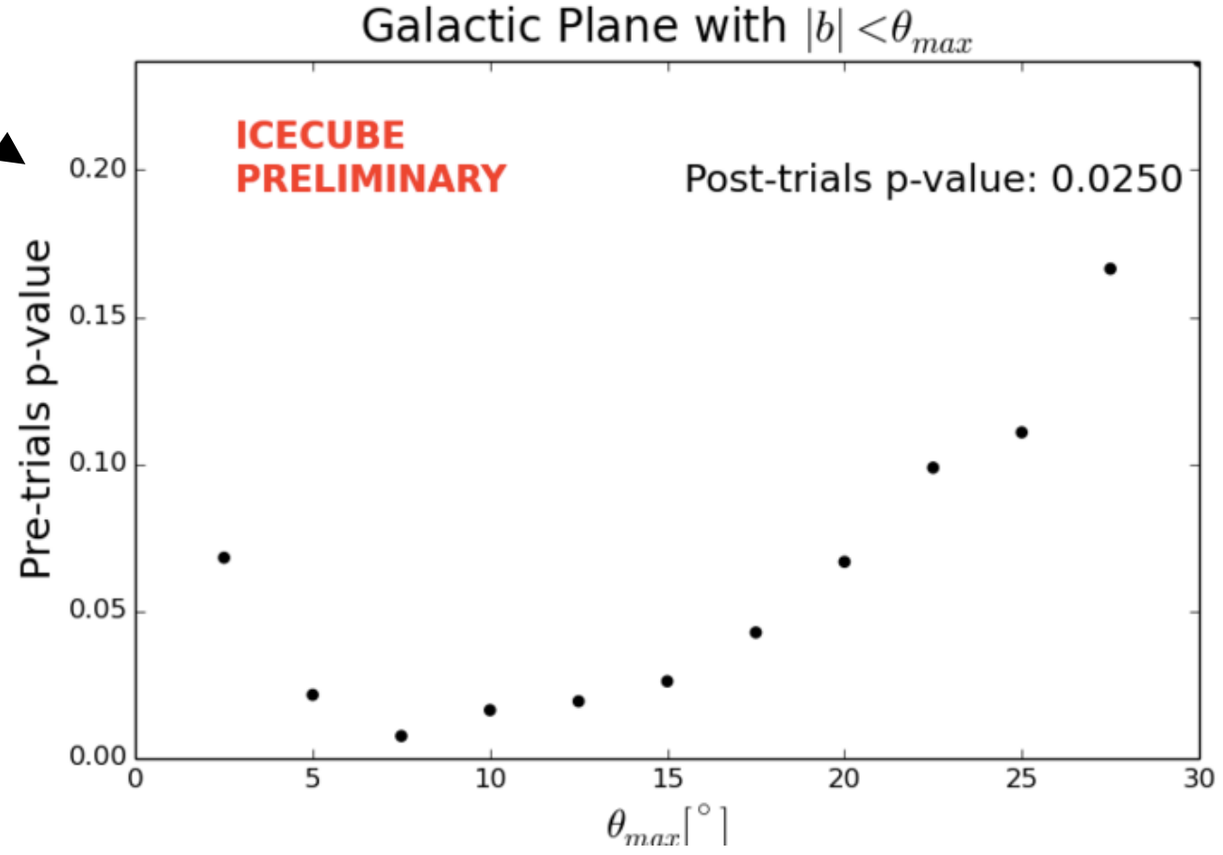
> Isotropic source distribution assumed.

Do we see neutrino emission from the Galactic plane ?

Low significance Galactic plane excess.

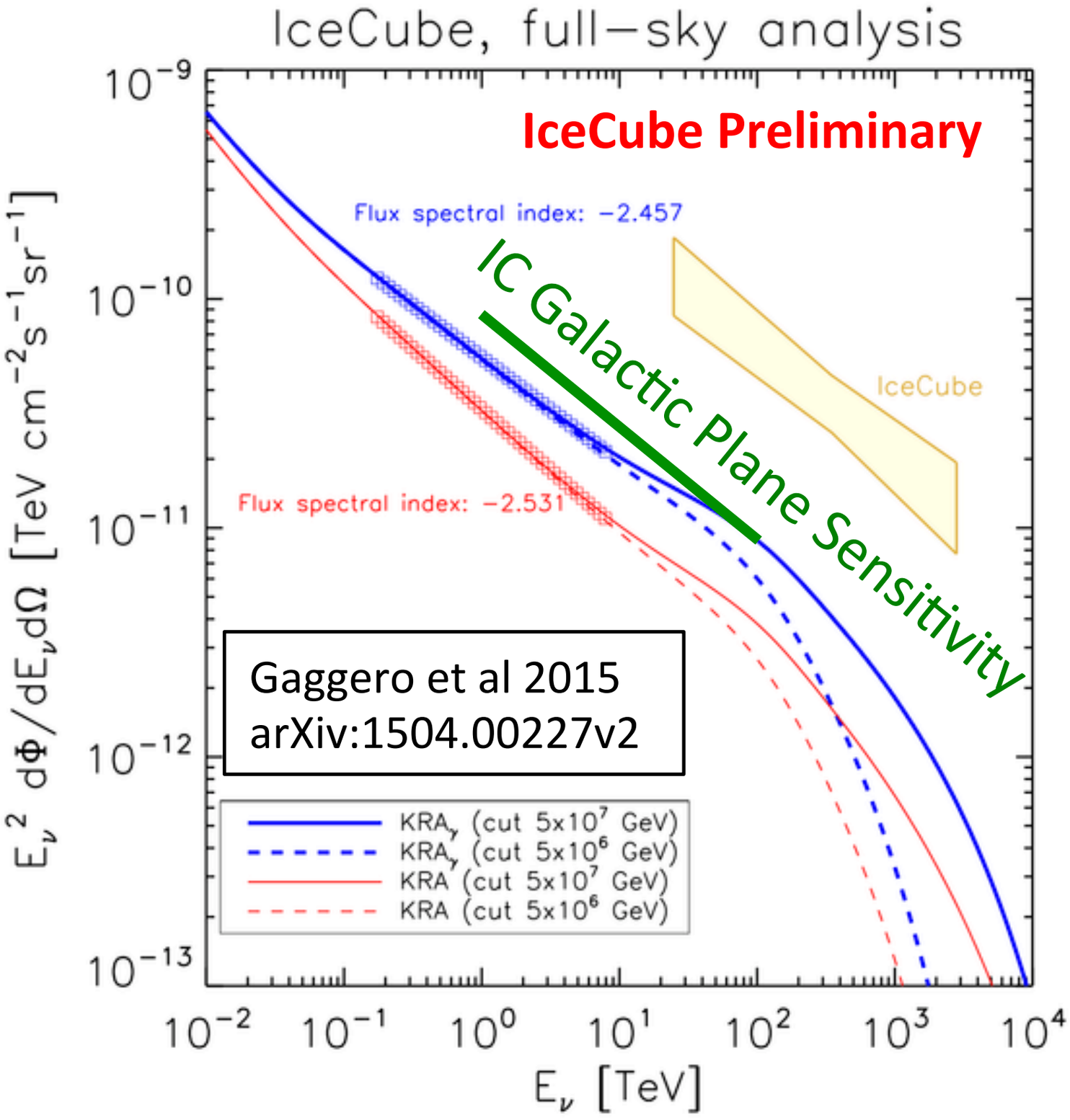






- Observed inside / outside the IceCube collaboration at 2σ / 3σ level.
- Analysis methods / energy thresholds are different between both analyses

More sensitive search with large sample of muon tracks….



> **7 years** of IceCube data

> Sensitive at lower energies.

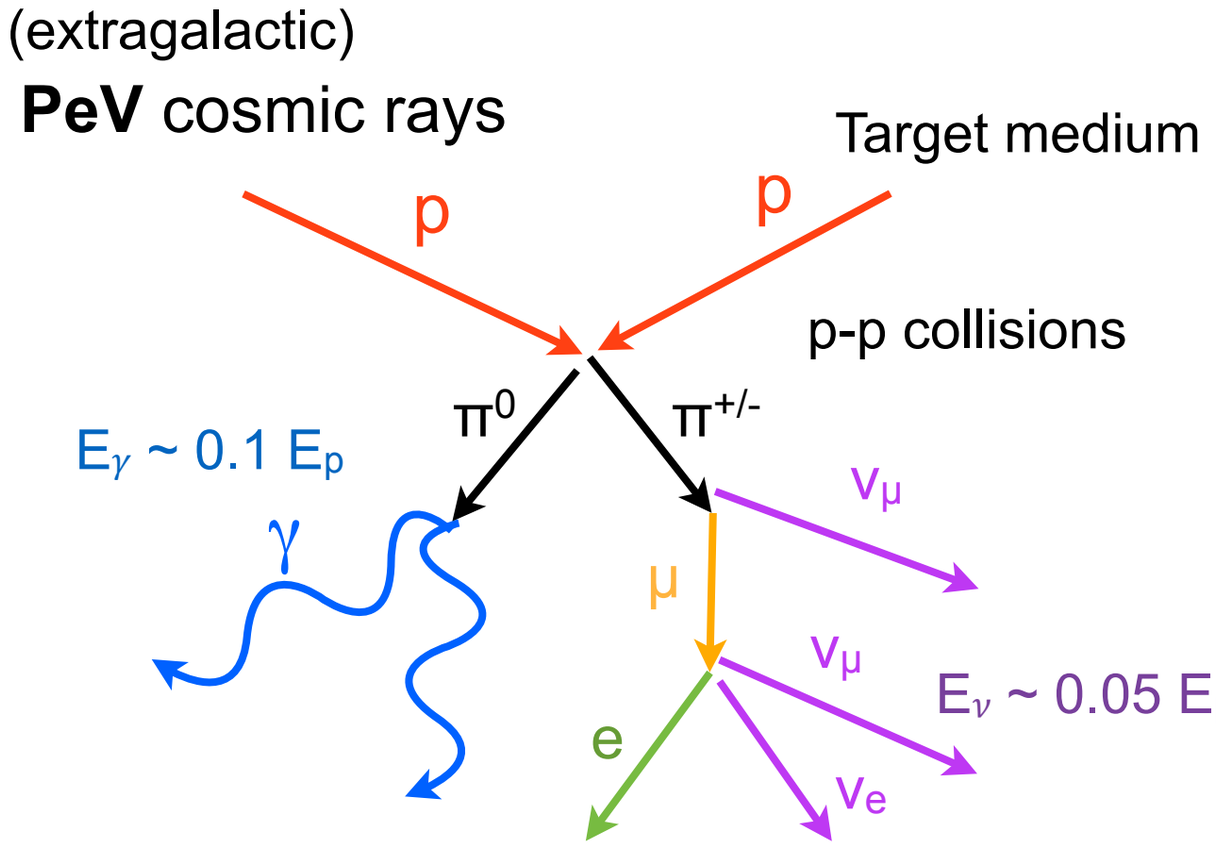
> No correlation to Galactic plane found found.

What are the extragalactic candidates?

… let’s look at gamma rays

The cosmic-ray / gamma / neutrino connection

- Cosmic rays interact with a target medium close to the source.
- ν / γ - production via p-p or p-γ collisions
- Reprocessing of γ rays to GeV energies.



TeV-PeV Neutrinos

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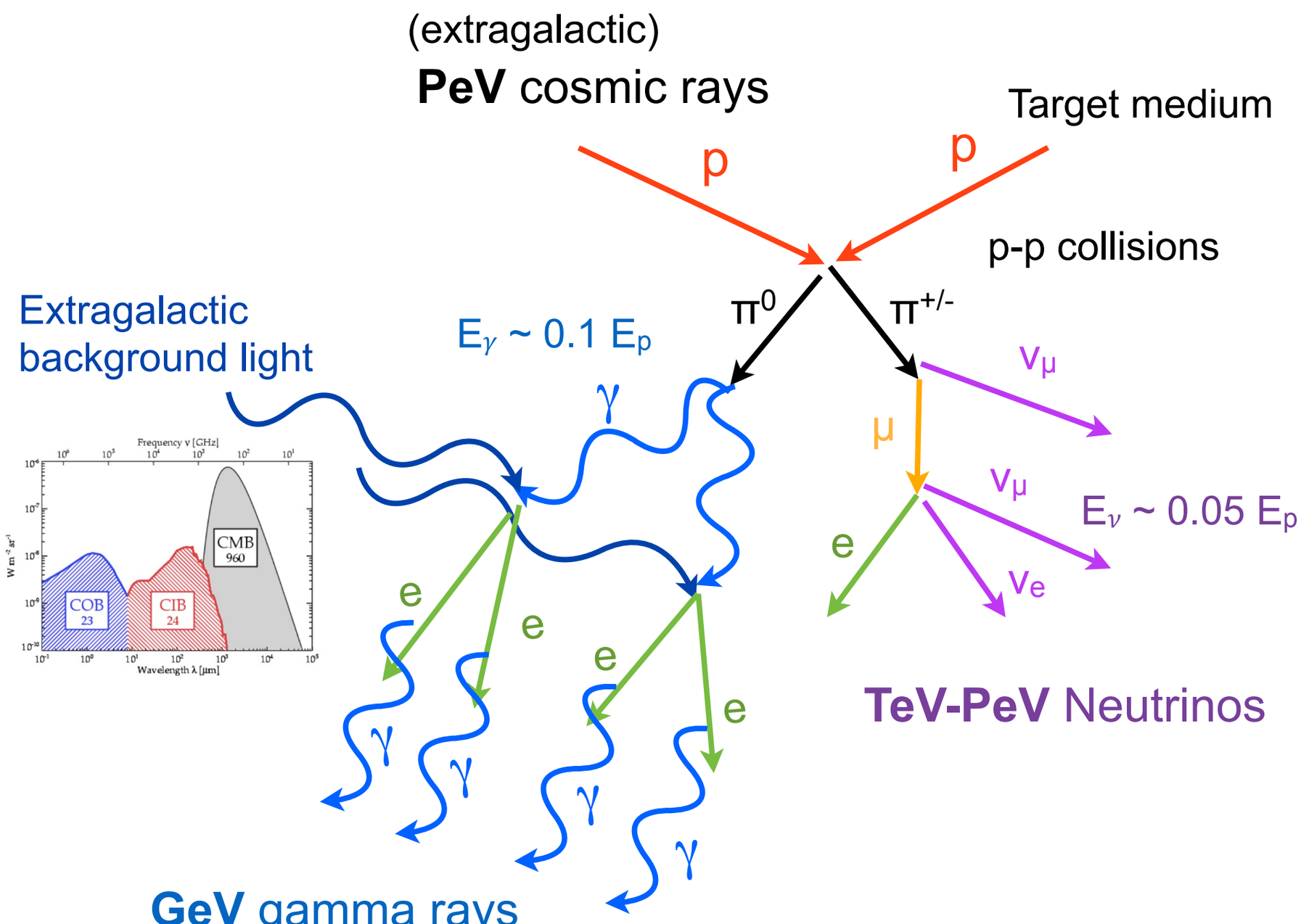
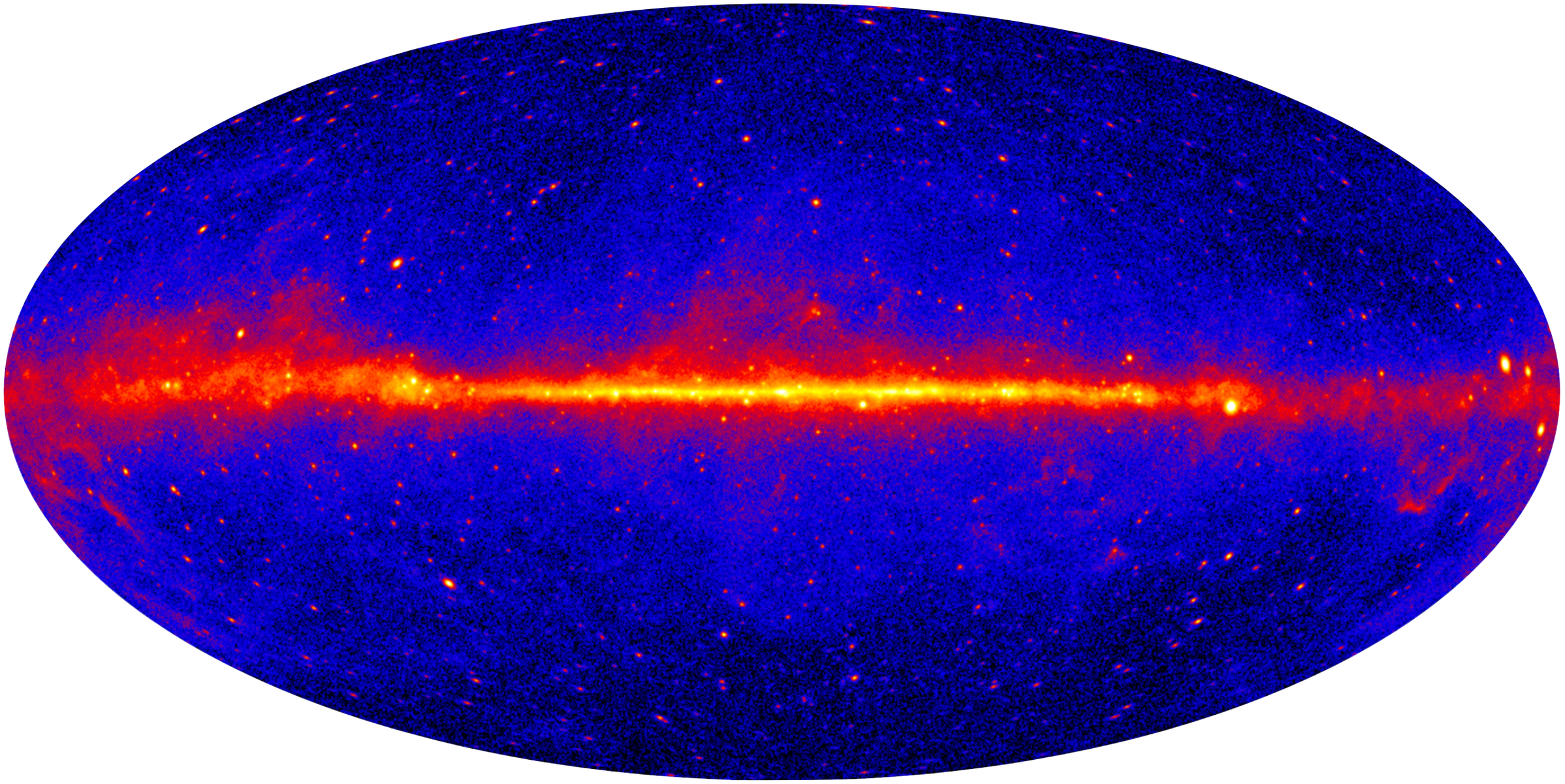


The GeV gamma-ray sky

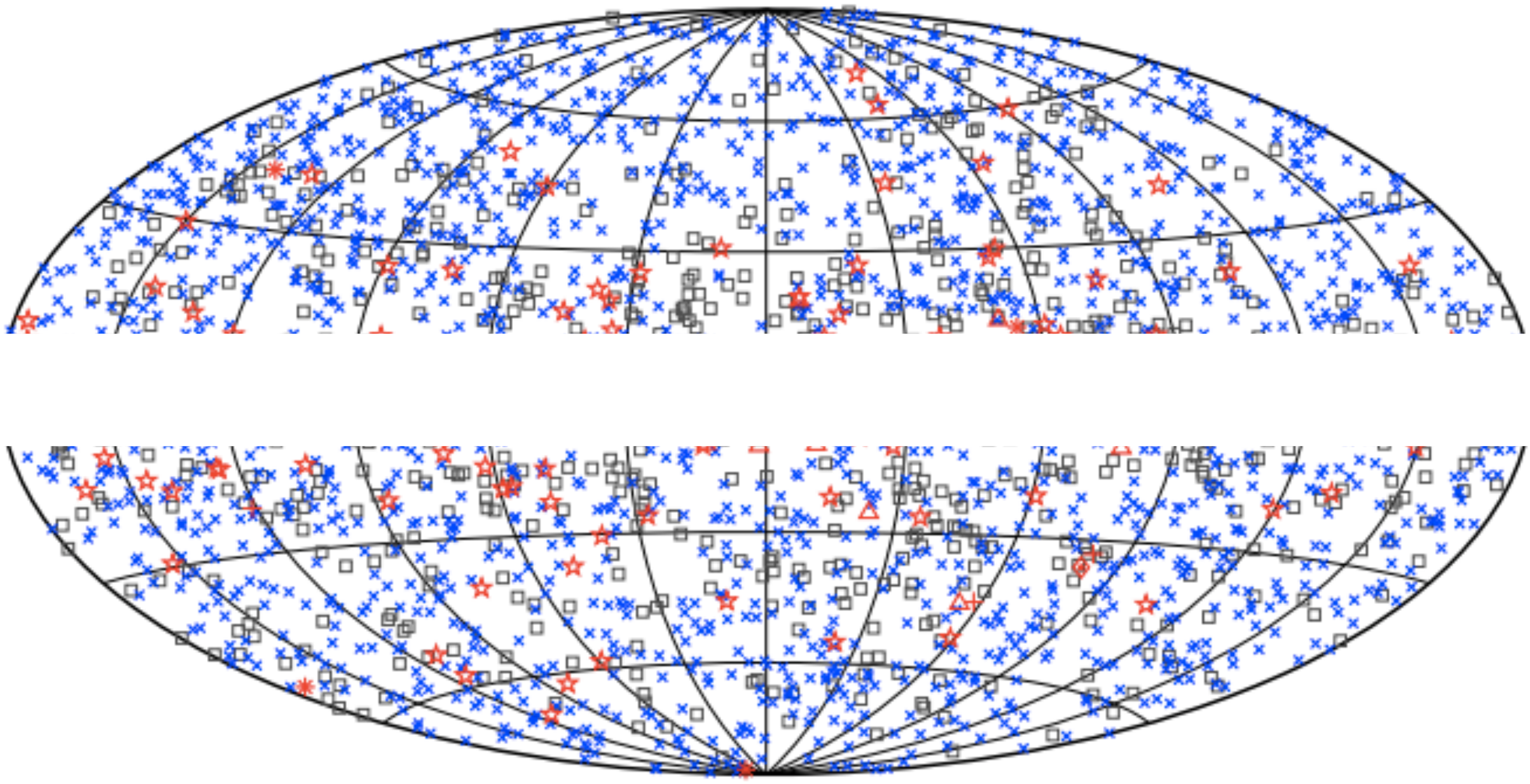
Fermi LAT, E > 1 GeV



> The most complete census of the non-thermal universe is the Fermi LAT sky survey at GeV energies.

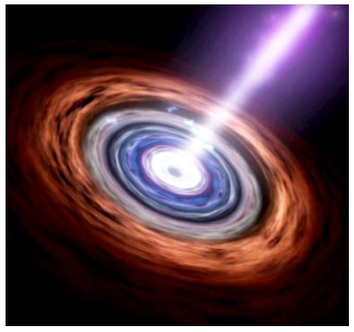
The GeV gamma-ray sky

Fermi LAT, E > 1 GeV



> The most complete census of the non-thermal universe is the Fermi LAT sky survey at GeV energies.

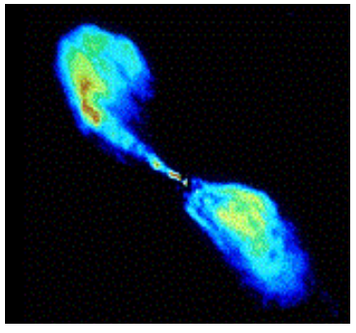
Extragalactic gamma-ray sources



Blazars

> Subtype of an active galaxy where jets are pointed at Earth.
> Quite rare, but very bright.

>2000 sources



(Misaligned) Active galaxies

> Galaxies with supermassive black holes at their centers.
> Observation of relativistic jets of high-energy particles.

~ 30 sources

Star-forming galaxies

> Normal galaxies (e.g. Milky Way).
> Very few neutrinos per Galaxy …but many Galaxies out there.

<10 sources

Gamma-ray bursts

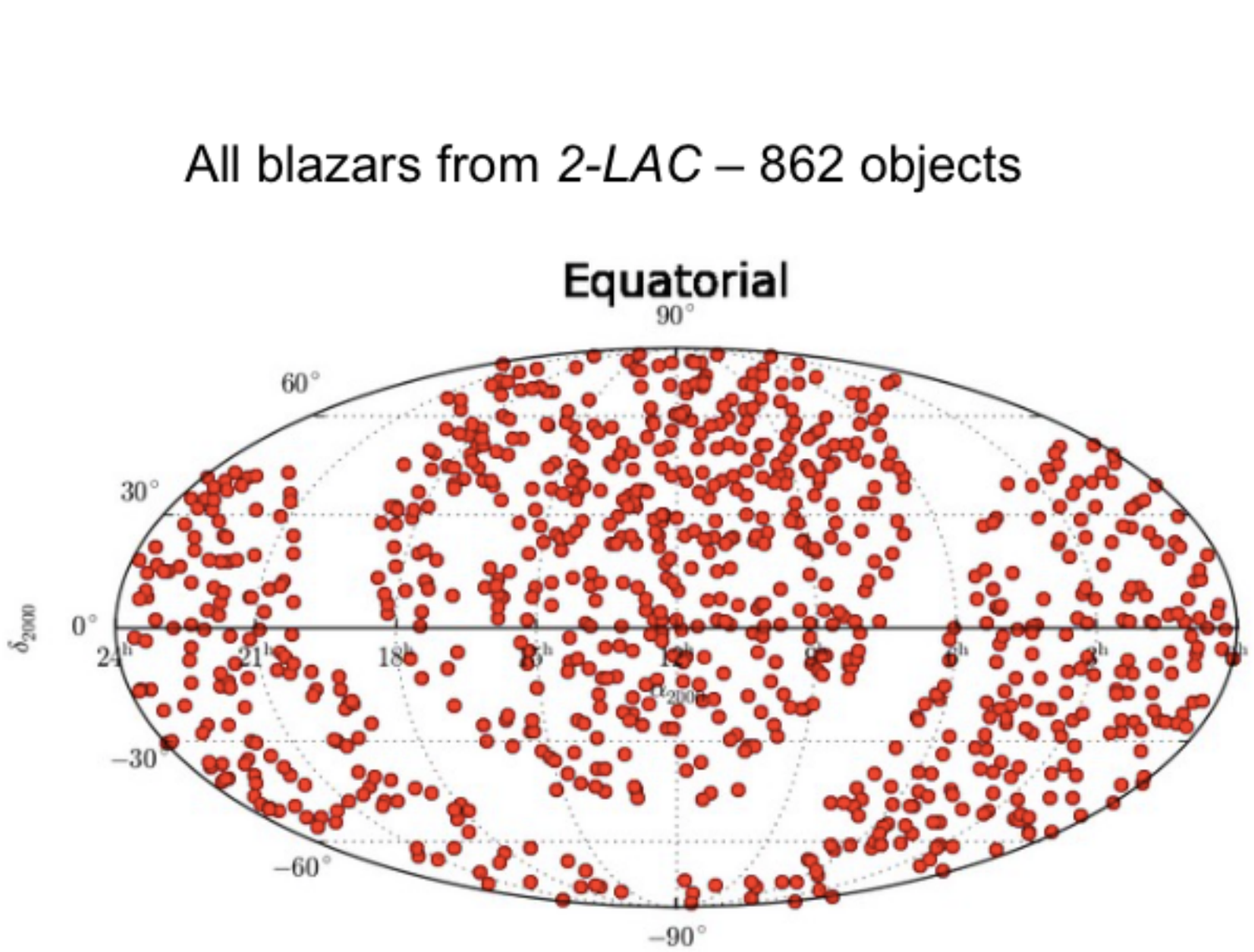
> Most violent explosions known.
> Likely related to explosions of massive stars or mergers of neutron stars/black holes.

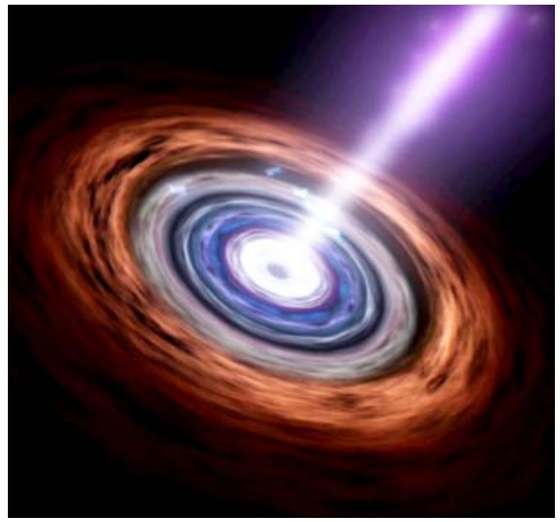
~250 / year

Search for correlation of ν to the sample of GeV Blazars.

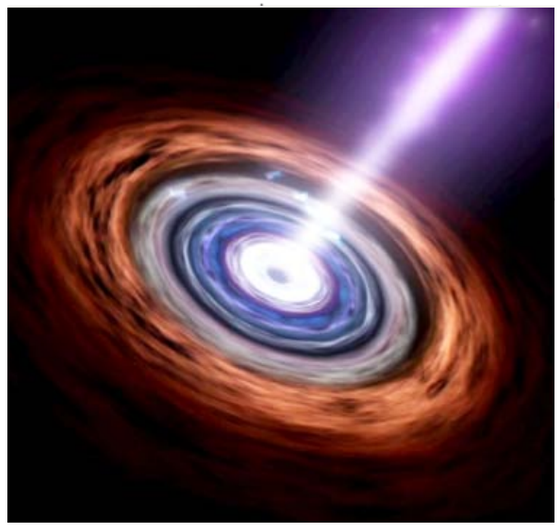
> Most of the extragalactic gamma-ray emission in the GeV band is from **Blazars.**

> Search for neutrino emission **spatially coincident with 2LAC Blazar** sample.



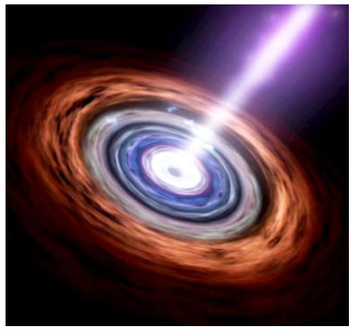


Extragalactic gamma rays and neutrinos.



> Fermi Blazars are **NOT** responsible for most of the observed ν's.

Extragalactic gamma-ray sources

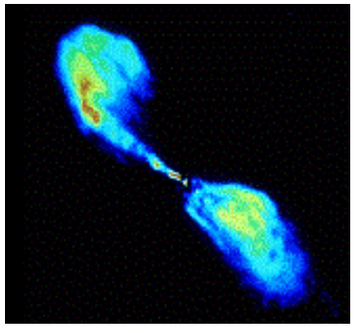


Blazars

> Subtype of an active galaxy where jets are pointed at Earth.
> Quite rare, but very bright.

>2000 sources

…. as dominant ν source population



(Misaligned) Active galaxies

> Galaxies with supermassive black holes at their centers.
> Observation of relativistic jets of high-energy particles.

~ 30 sources

Star-forming galaxies

> Normal galaxies (e.g. Milky Way).
> Very few neutrinos per Galaxy …but many Galaxies out there.

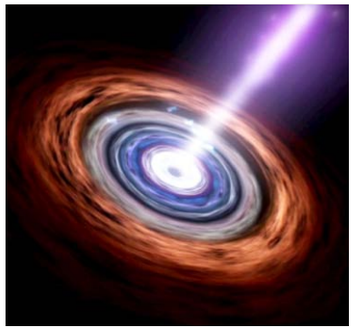
<10 sources

Gamma-ray bursts

> Most violent explosions known.
> Likely related to explosions of massive stars or mergers of neutron stars/black holes.

~250 / year

Extragalactic gamma-ray sources



Blazars

> Subtype of an active galaxy where jets are pointed at Earth.
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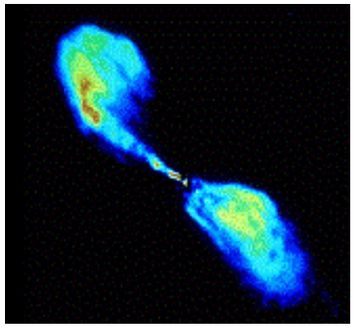
…. as dominant v source population



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> Observation of relativistic jets of high-energy particles.

~ 30 sources

Star-forming galaxies

> Normal galaxies (e.g. Milky Way).
> Very few neutrinos per Galaxy …but

No significant detection

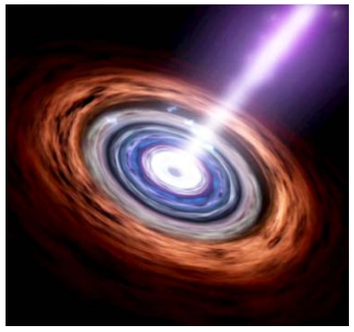
of any GRB or fast and bright v transient.

Gamma-ray bursts

> Most violent explosions known.
> Likely related to explosions of massive stars or mergers of neutron stars/black holes.

~250 / year

Extragalactic gamma-ray sources



Blazars

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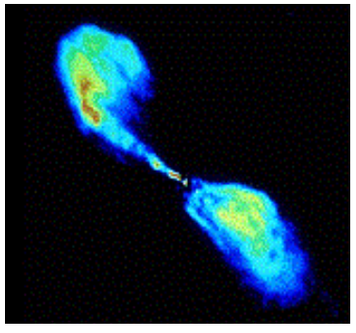

(Misaligned) Active galaxies

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> Normal galaxies (e.g. Milky Way).
> Very few neutrinos per Galaxy …but many Galaxies out there.

<10 sources

Hard to reconcile with observed gamma-ray emission

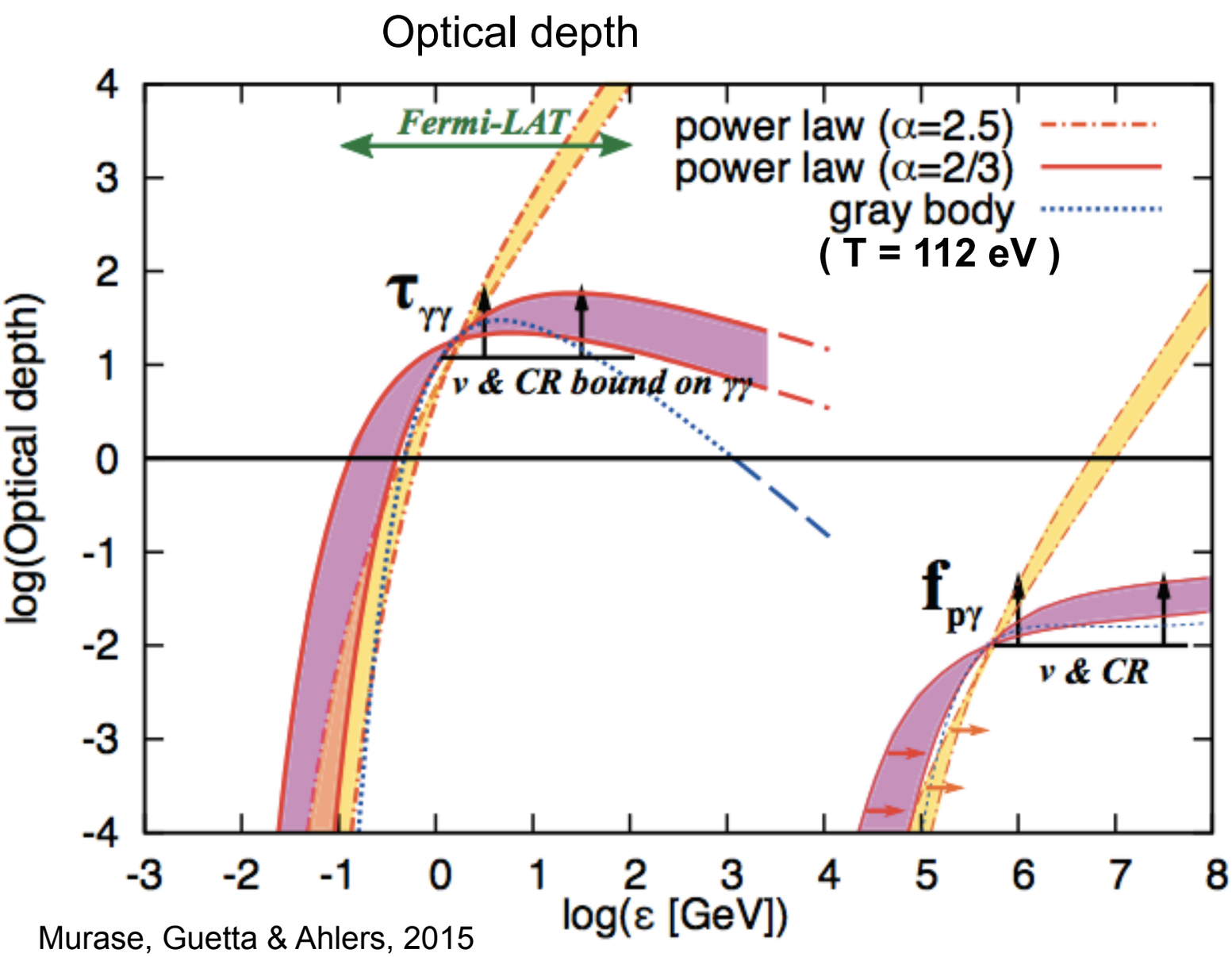
Gamma-ray bursts

> Most violent explosions known.
> Likely related to explosions of massive stars or mergers of neutron stars/black holes.

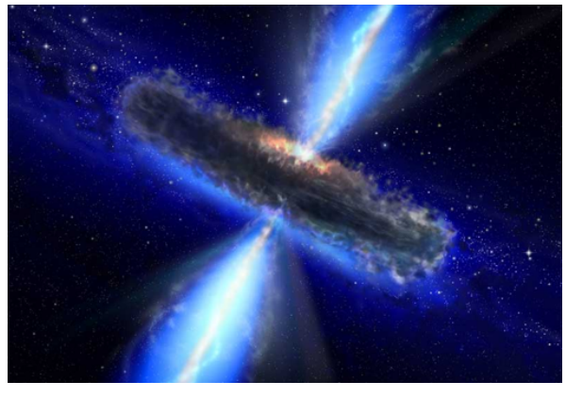
~250 / year

What remains ?

Gamma-ray opaque sources



Murase, Guetta & Ahlers, 2015



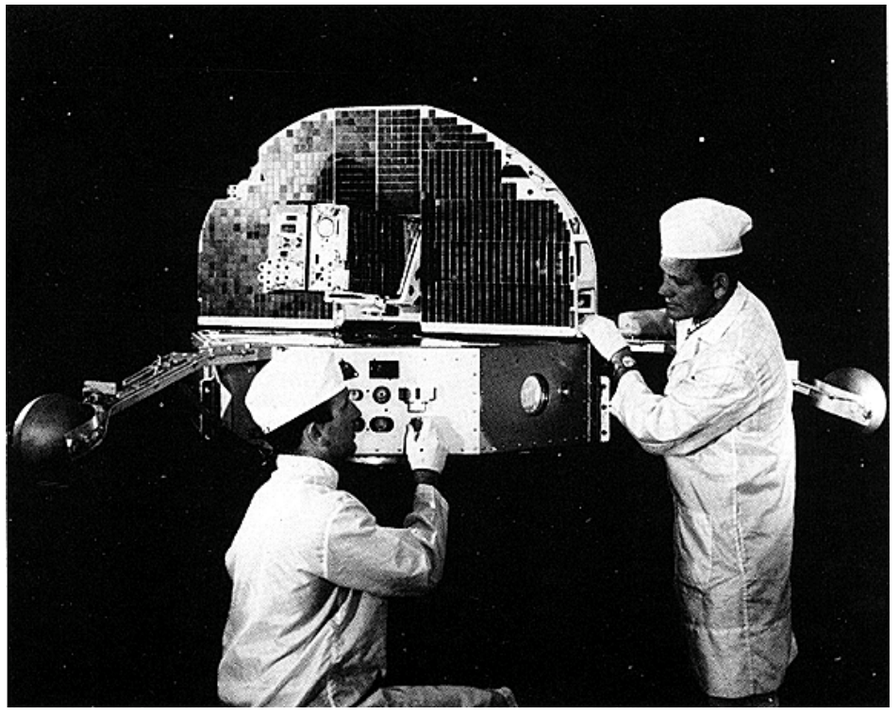
- Sources that efficiently absorb gamma rays in the GeV band:
- Accretion disks of AGNs
- Core-collapse supernovae
- etc.
- **The neutrino sky is very different to the gamma-ray sky!**

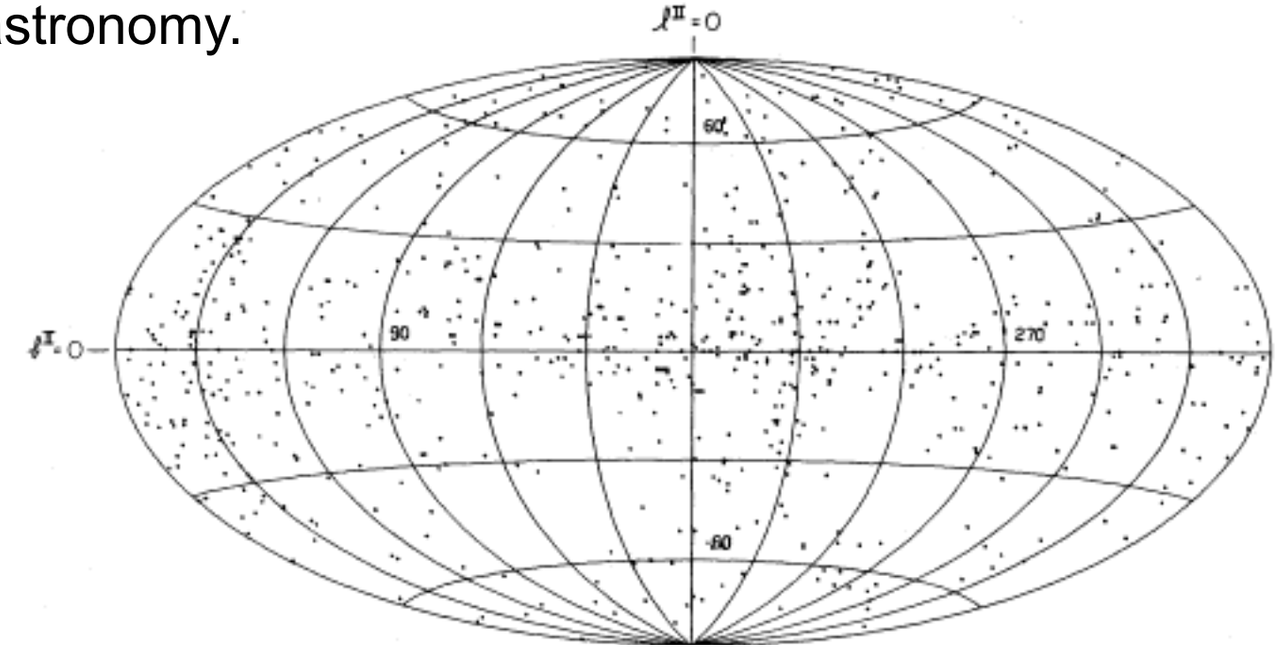
Where do we go from here ? *

* besides collecting 10 more years of great IceCube data.

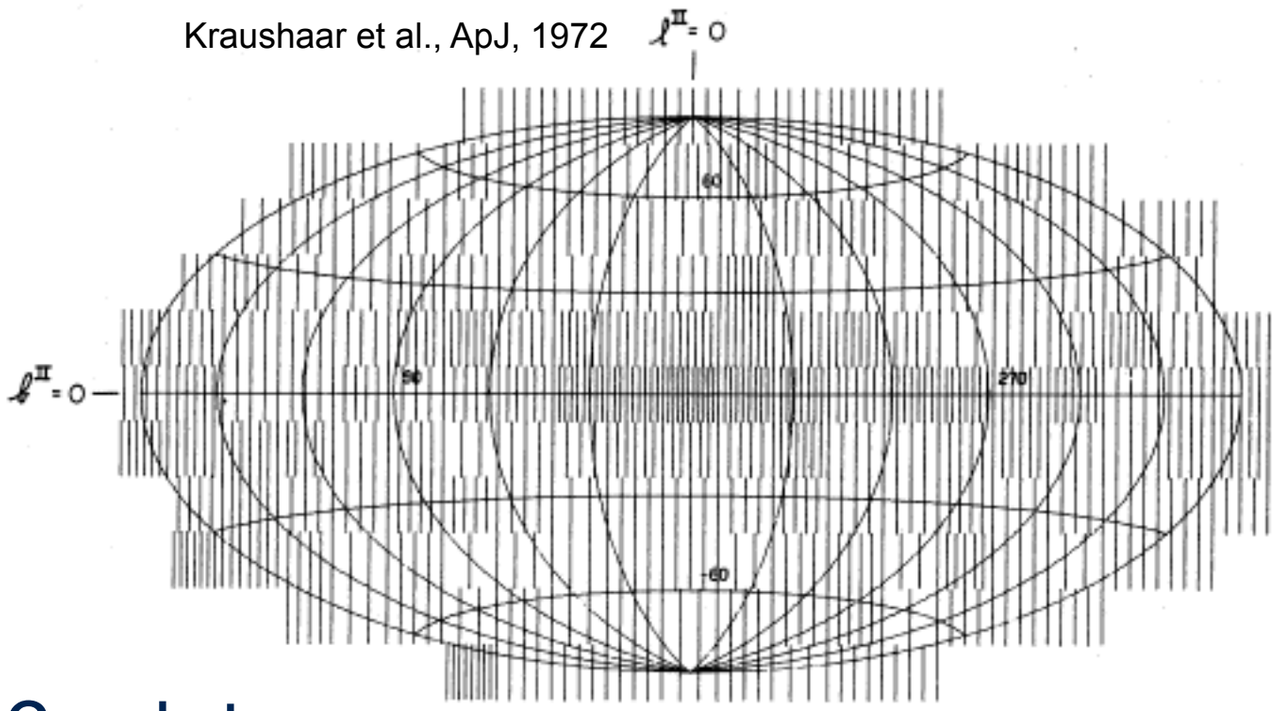
This is where we are now in neutrino astronomy….

… comparing to the history of gamma-ray astronomy.





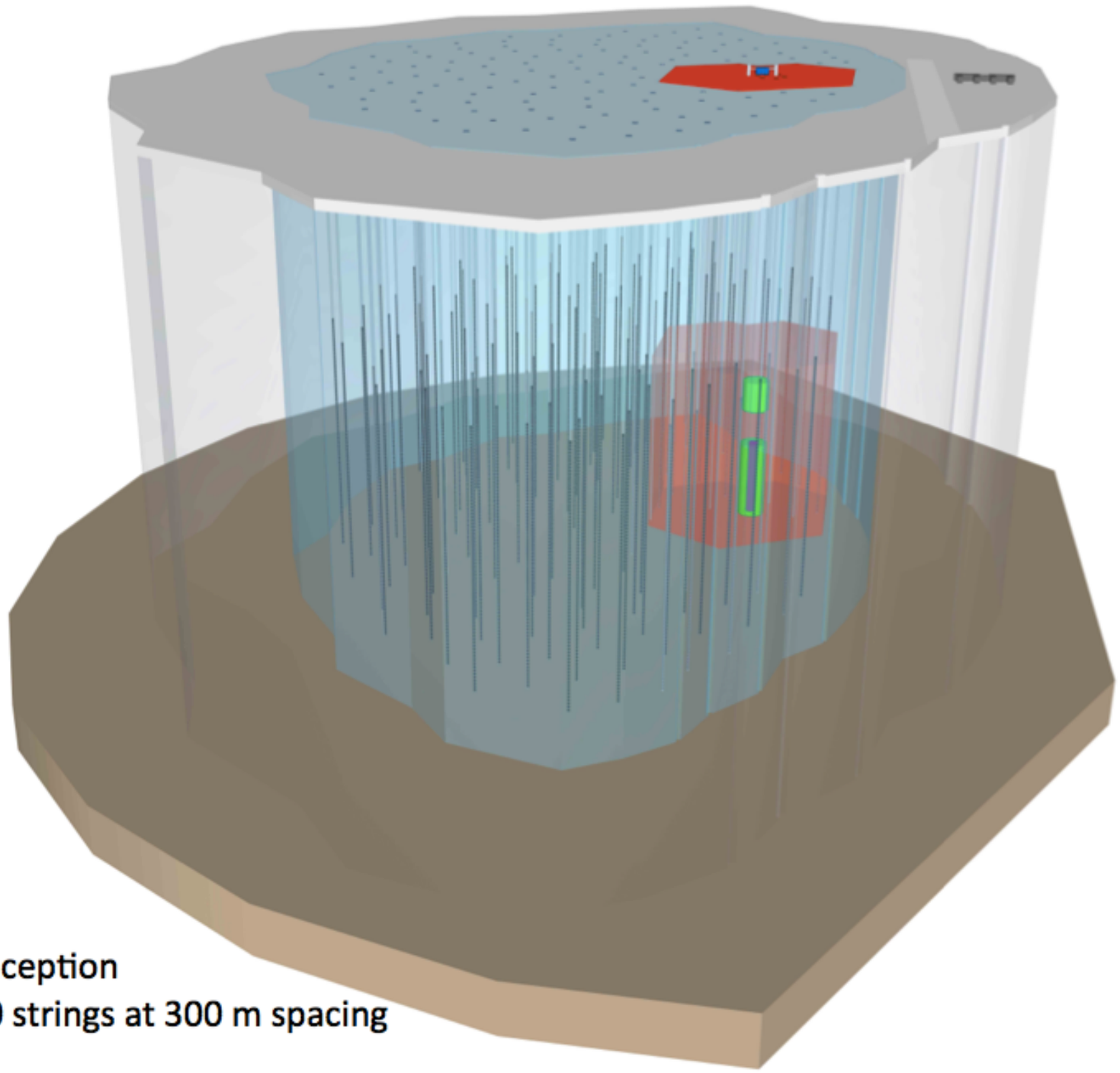
Kraushaar et al., ApJ, 1972



- OSO-3 launched 1967 on a Delta C rocket
- 621 photons above 50 MeV detected.
- No sources, but Galactic plane emission identified.

We need to make the next step: IceCube-Gen2.

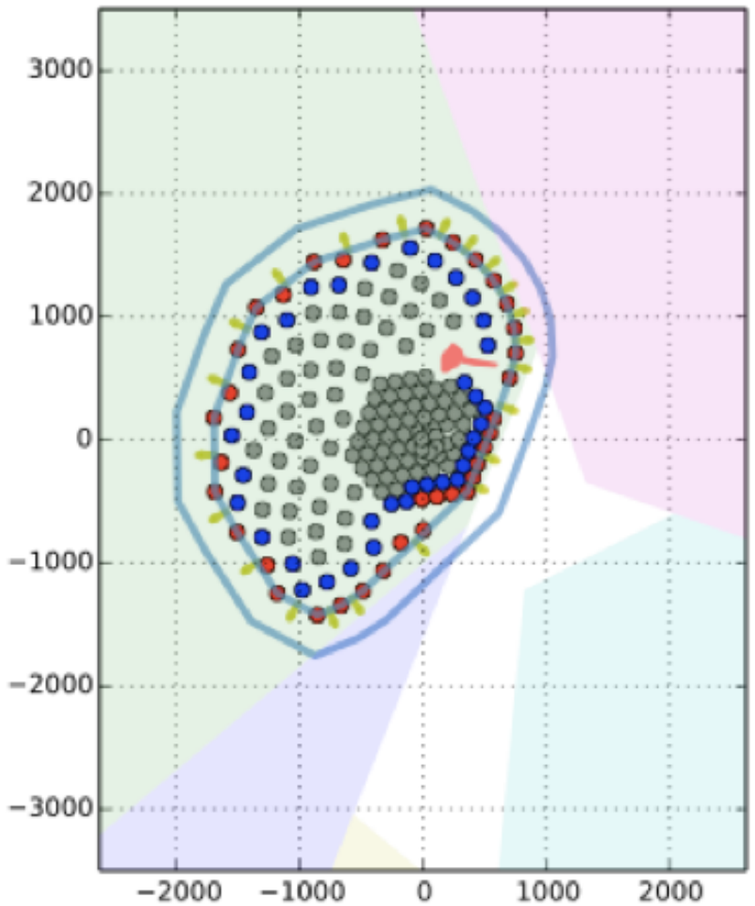
> Design options evaluated for a proposal to funding agencies.



Artist conception
Here: 120 strings at 300 m spacing

> Design option:

- About **100 new strings**.
- ~ **5 km²** surface area.
- ~ **7 km³** volume.
- > **5 x** IceCube sensitivity.



Summary.

> The first few years of neutrino astronomy are behind us.

> We are making quick progress in determining the properties of the cosmic neutrino signal.

> A substantial fraction of the neutrino flux seems to be extragalactic.

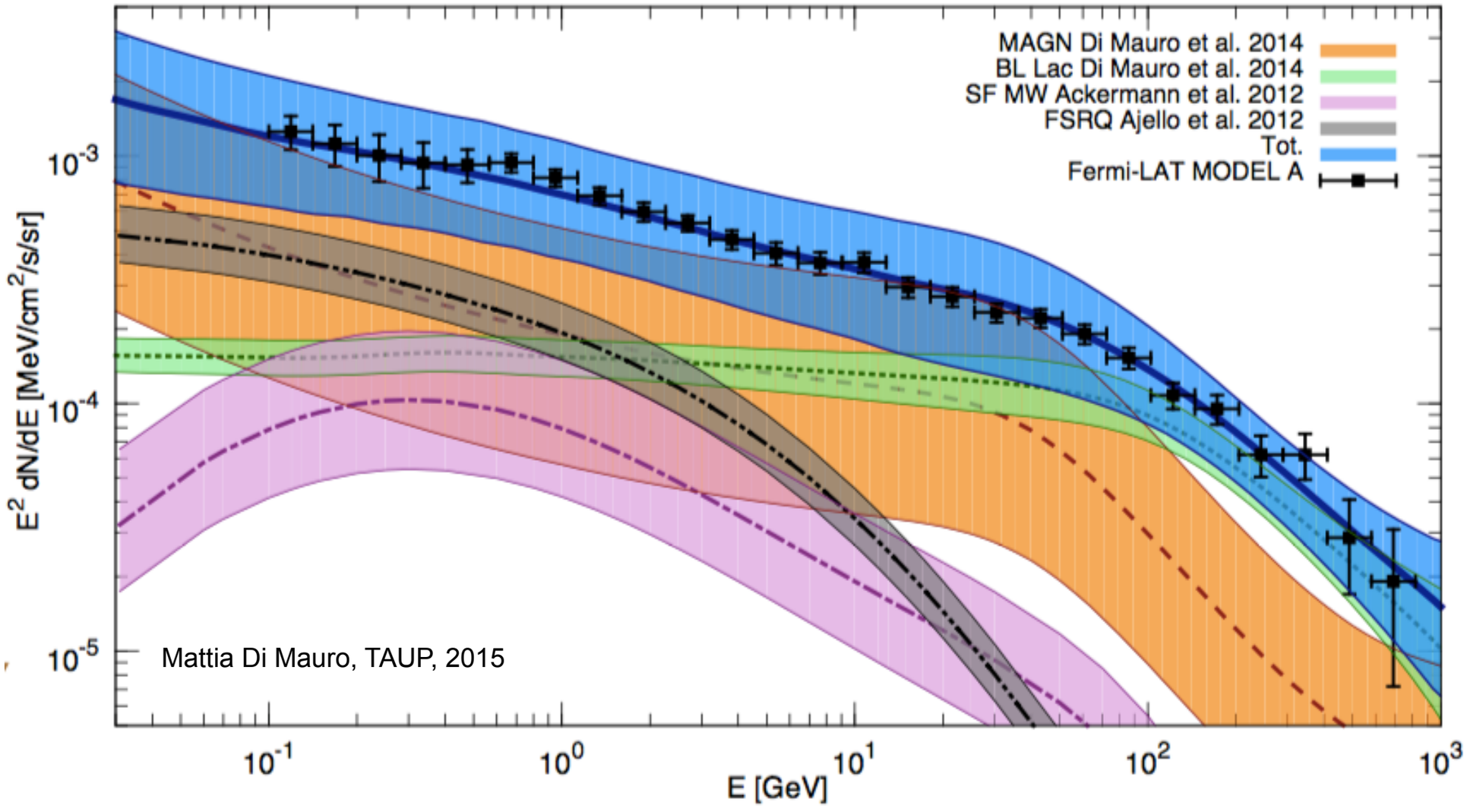
> Many (weaker) sources need to contribute to explain the absence of point sources.

> There are first indications that the neutrino sky is substantially different from the GeV gamma-ray sky.

… and there is a lot of great science with neutrino telescopes I didn't show today.

Backup.

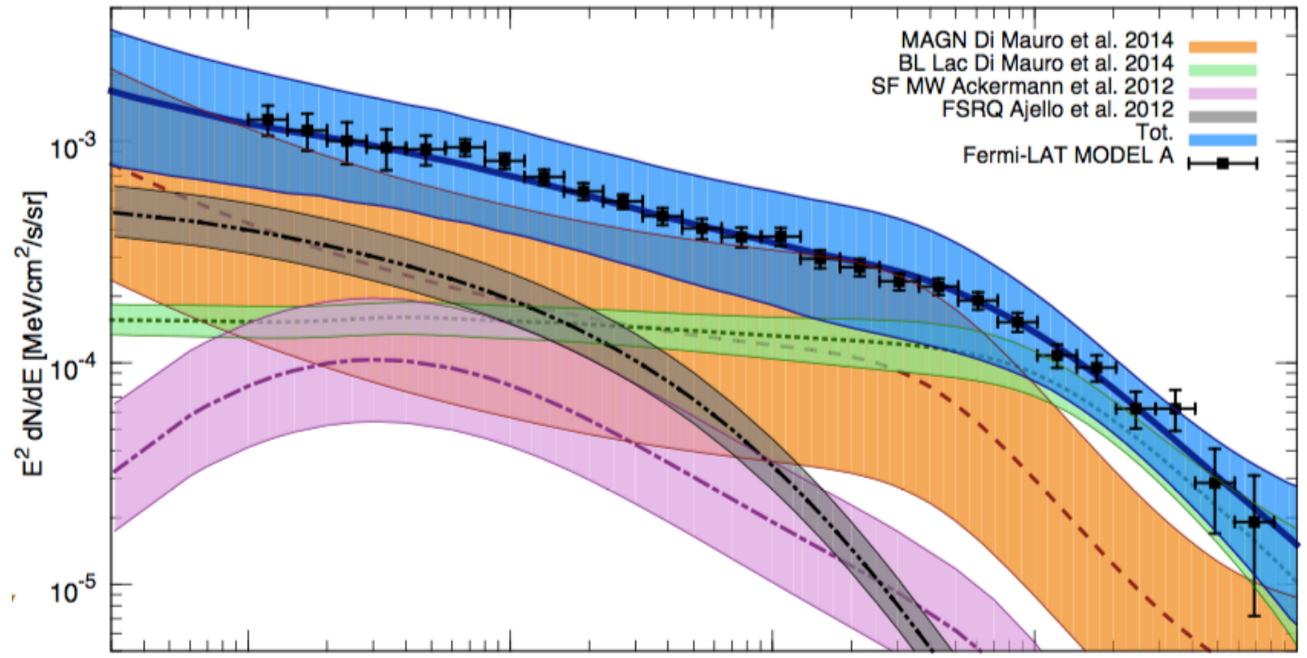
Extragalactic gamma-ray emission.



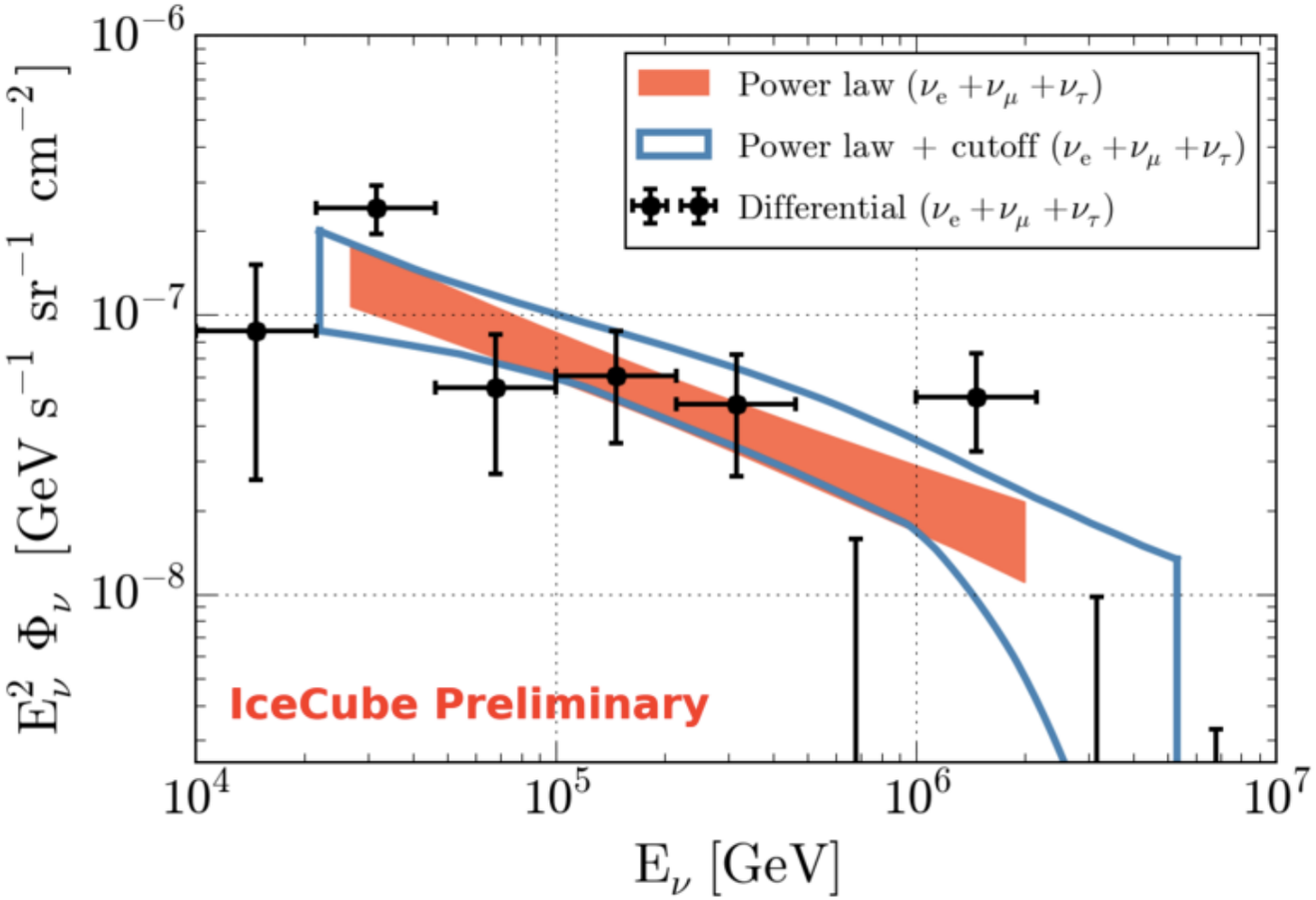
- Contribution from unresolved sources can be estimated.
- Most of the extragalactic gamma-ray emission above 10 GeV originates from Blazars.

Extragalactic gamma-ray and neutrino backgrounds.

> ….even though the spectral shape and energy flux is very similar



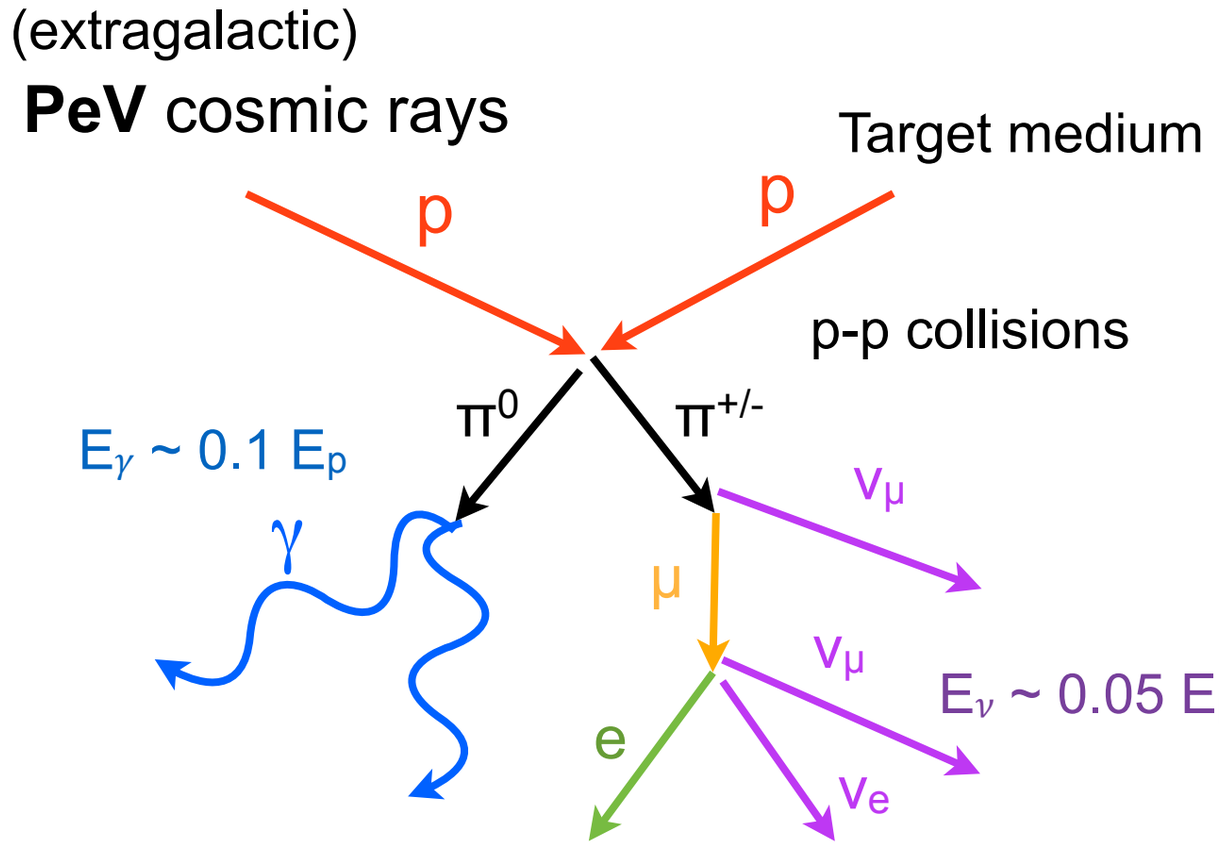
spectral index: **2.37 ± 0.13**
cutoff energy: **3.1 PeV**
energy flux above 10 TeV:
4.4 TeV cm^{-2} s^{-1}



spectral index: **2.30 ± 0.02**
cutoff energy: **350 GeV**
energy flux above 10 TeV:
7.1 TeV cm^{-2} s^{-1}

The cosmic-ray / gamma / neutrino connection

- Cosmic rays interact with a target medium close to the source.
- ν / γ - production via p-p or p-γ collisions
- Reprocessing of γ rays to GeV energies.



TeV-PeV Neutrinos

The cosmic-ray / gamma / neutrino connection

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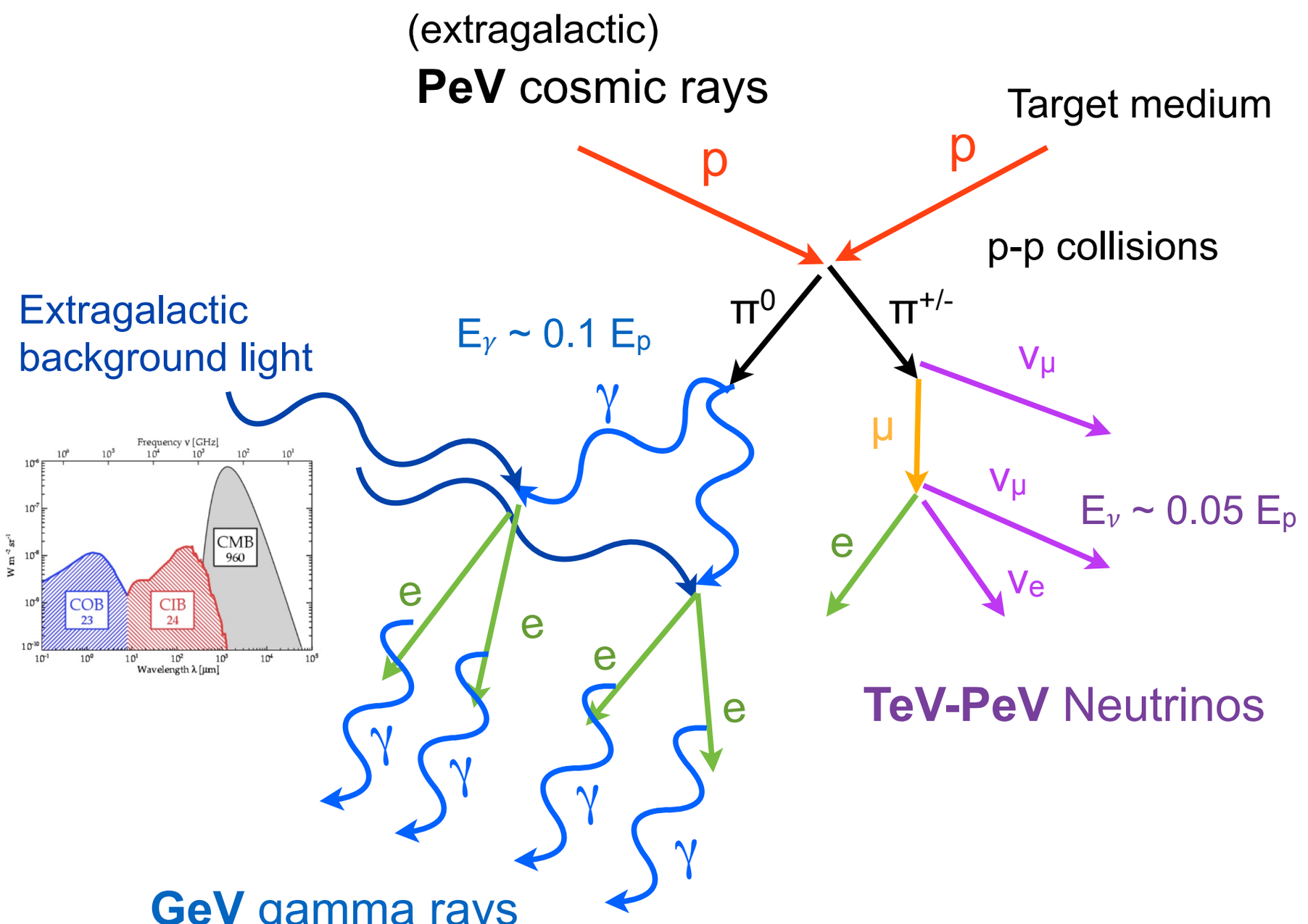

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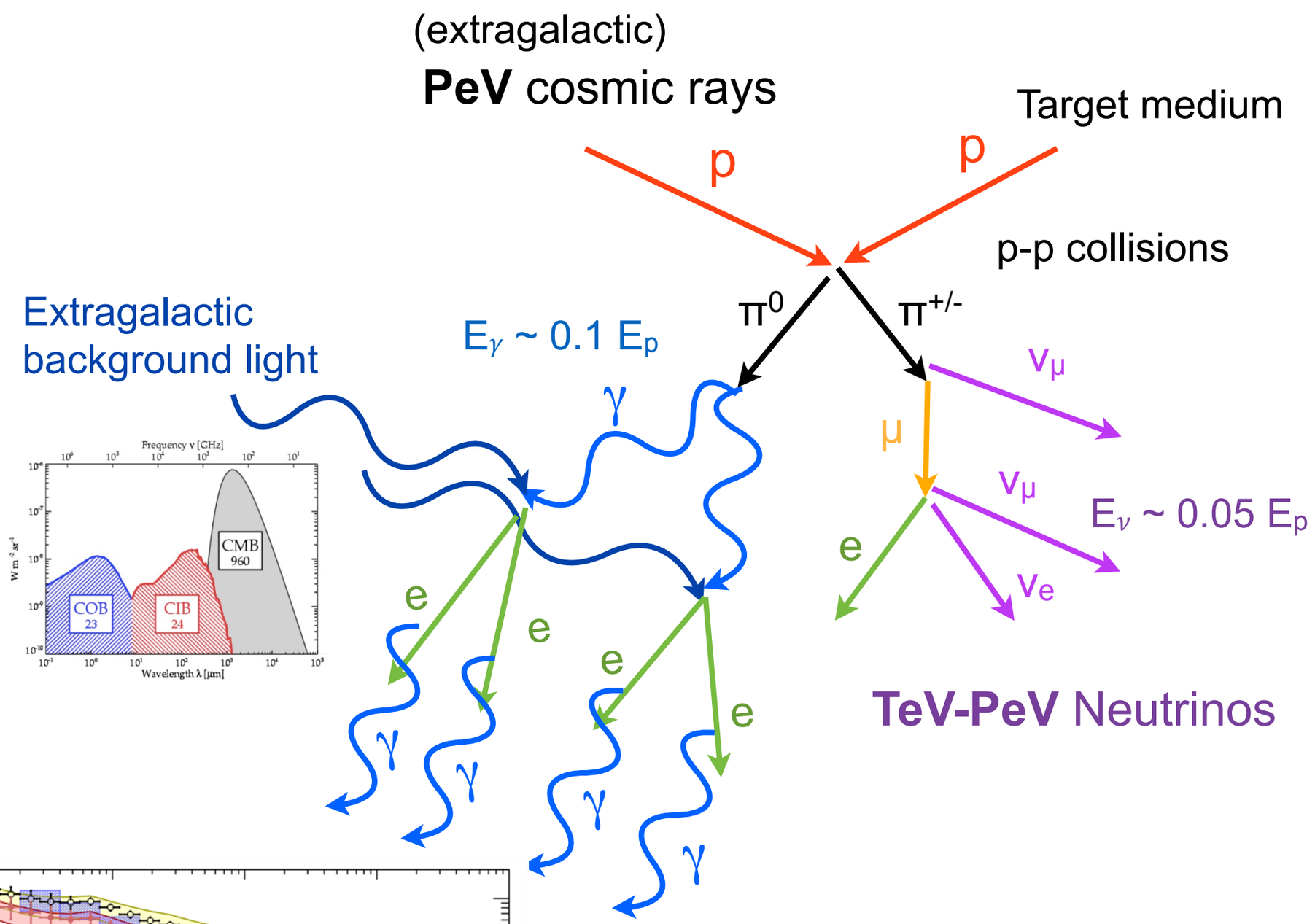
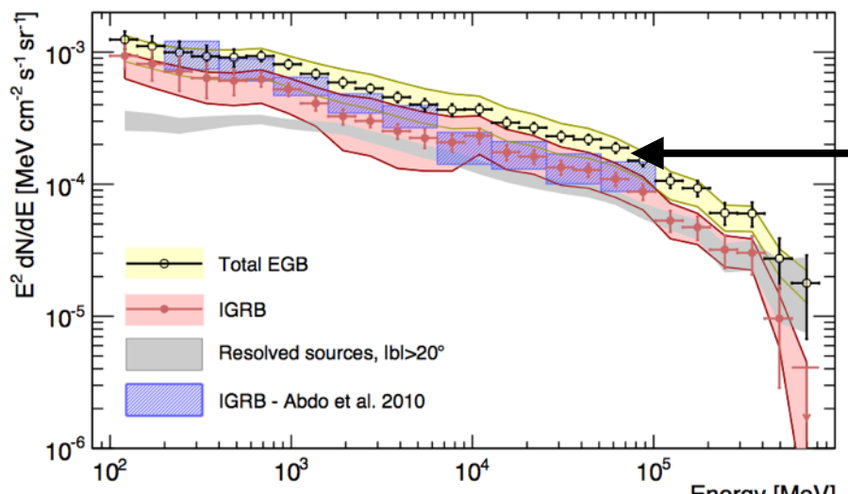
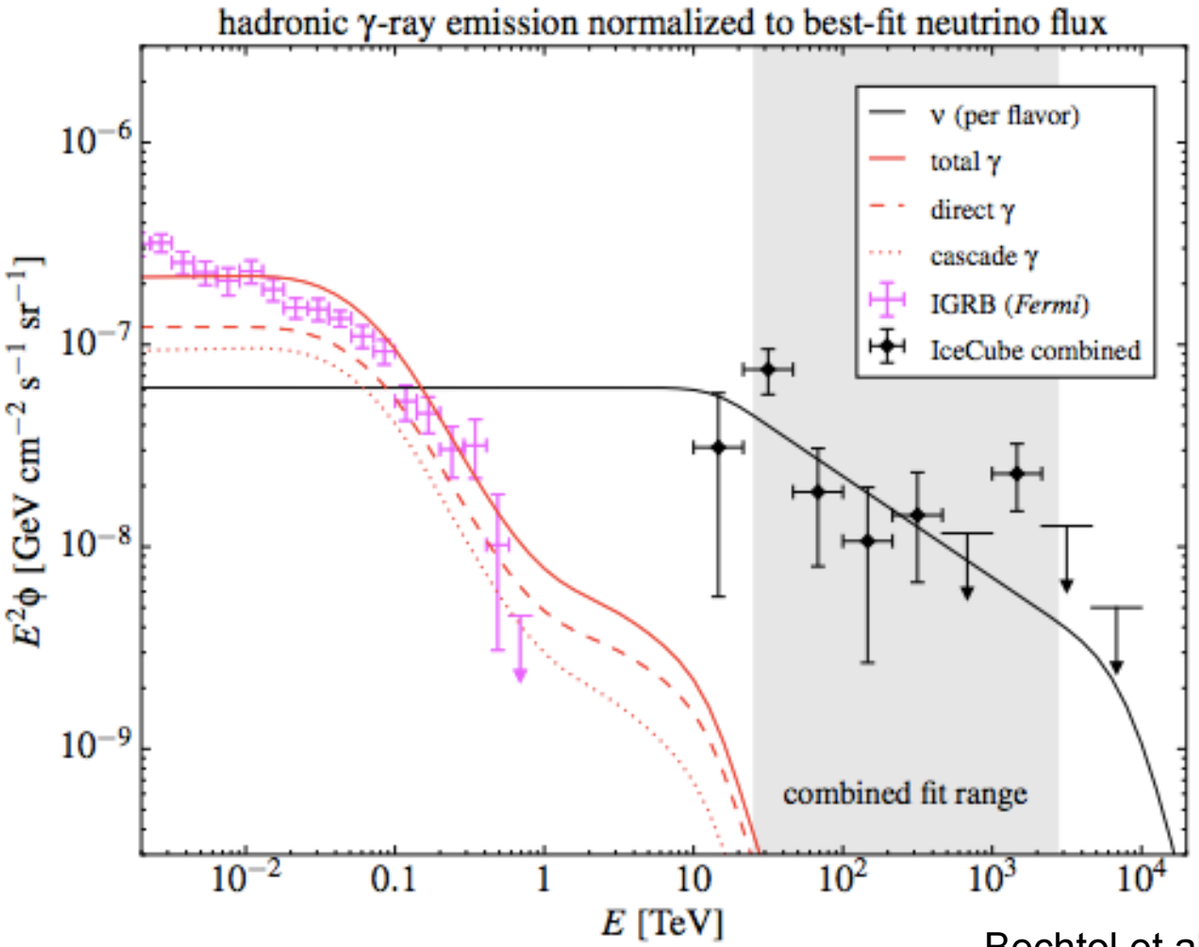
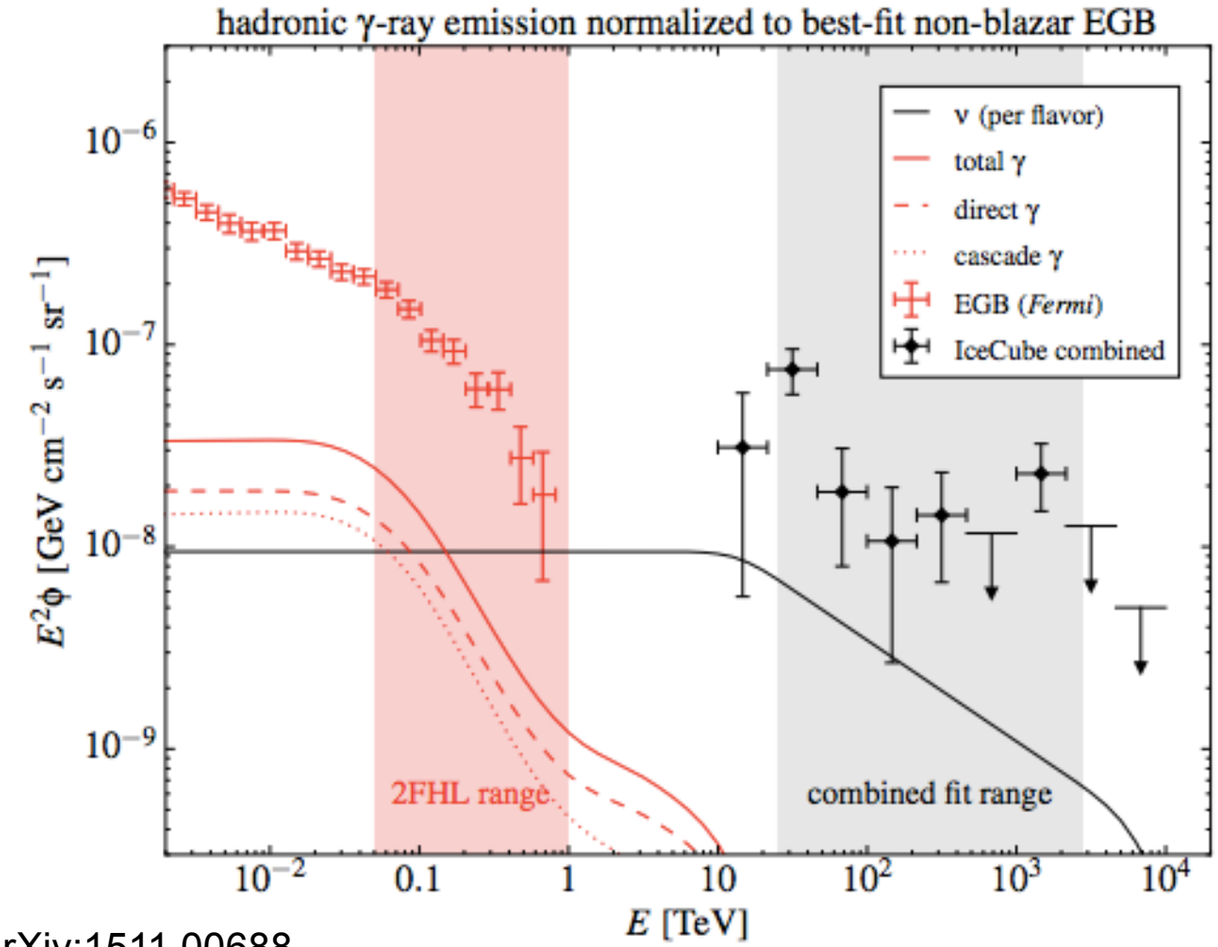




EGB is an upper bound on production mechanisms for extragalactic TeV-PeV neutrinos!

Neutrinos from star-forming galaxies.





Bechtol et al., arXiv:1511.00688

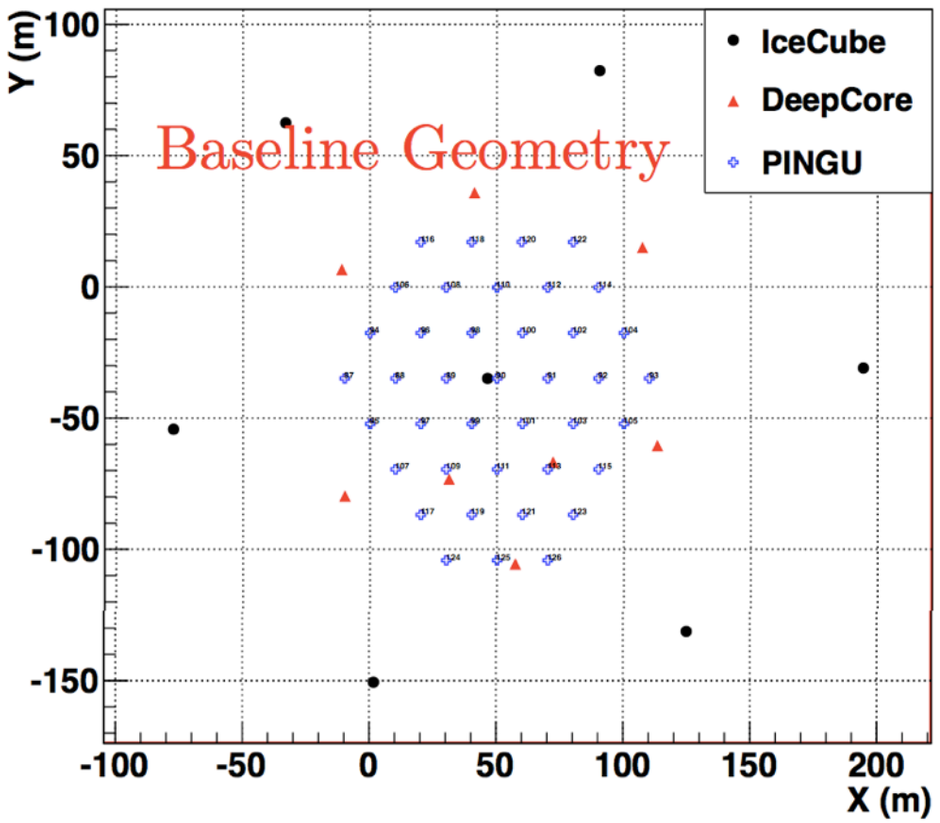
> Gamma-ray emission associated with star-forming galaxies would fill up entire EGB

> Contradicts findings that most of the EGB originates from Blazars.

PINGU: Measurements of fundamental neutrino properties.

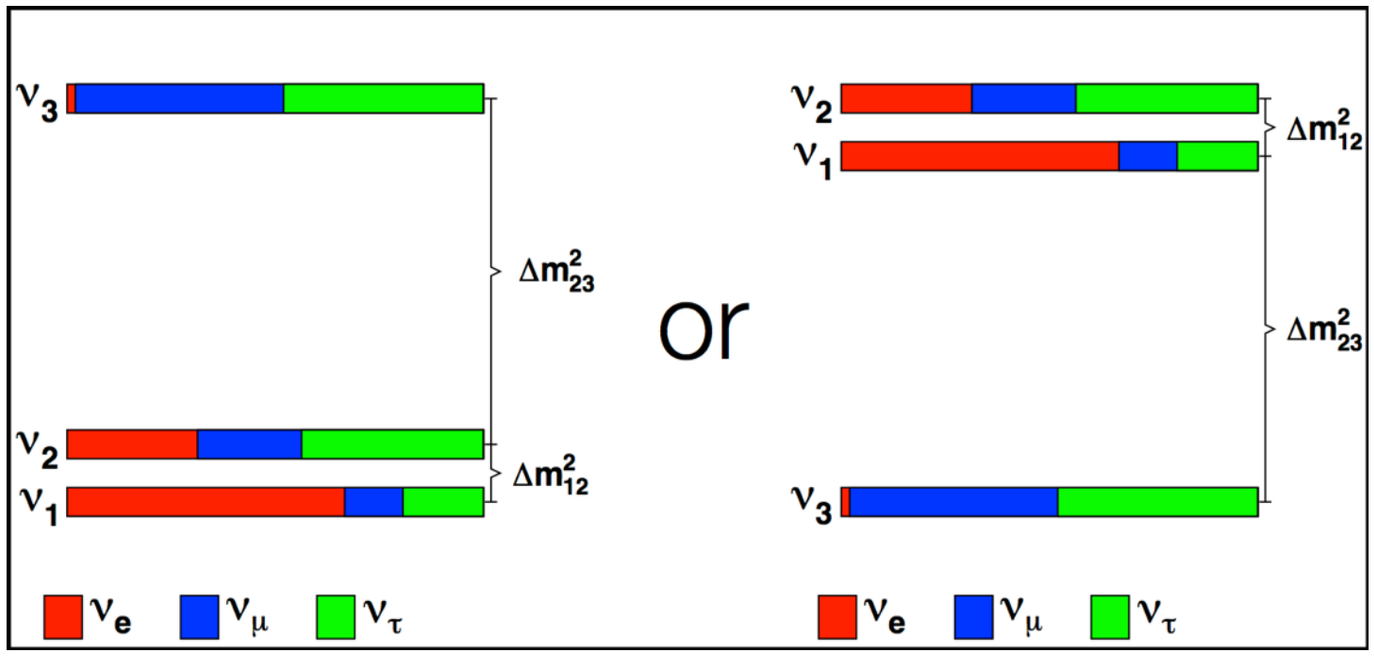
- **PINGU:** Add a densely instrumented core of IceCube.
  - 40 additional strings.

- **Lowers energy threshold** to few GeV.



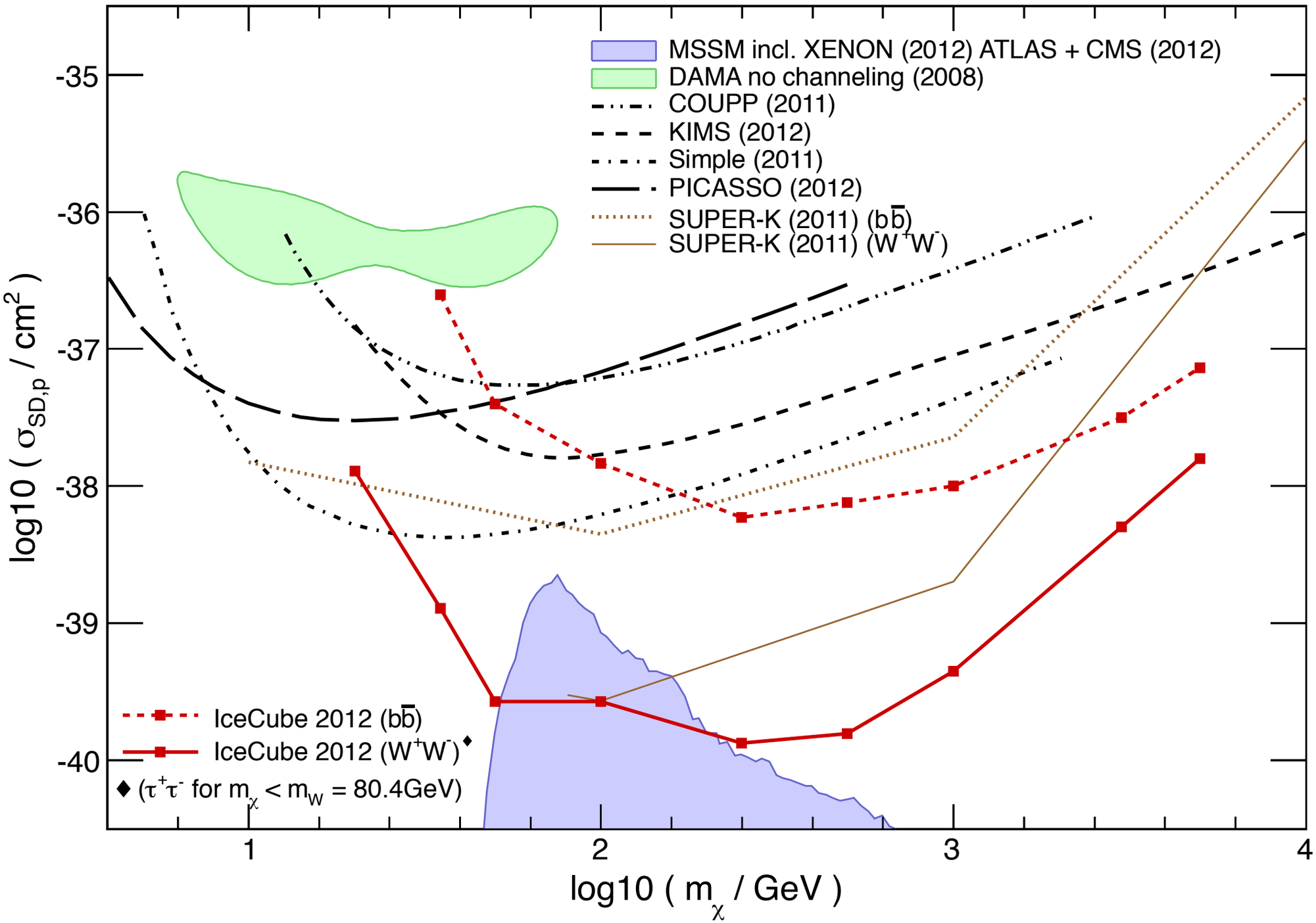
- Measurement of **fundamental neutrino properties:**
  - Oscillation parameters
  - Mass hierarchy

- 3σ determination of **mass hierarchy** in ~ 3.5 years.



Search for neutrino annihilations in the sun.

- Mass of sun is dominated by **hydrogen atoms**.
- World's best limits on **spin-dependent** scattering **cross-section** from IceCube.



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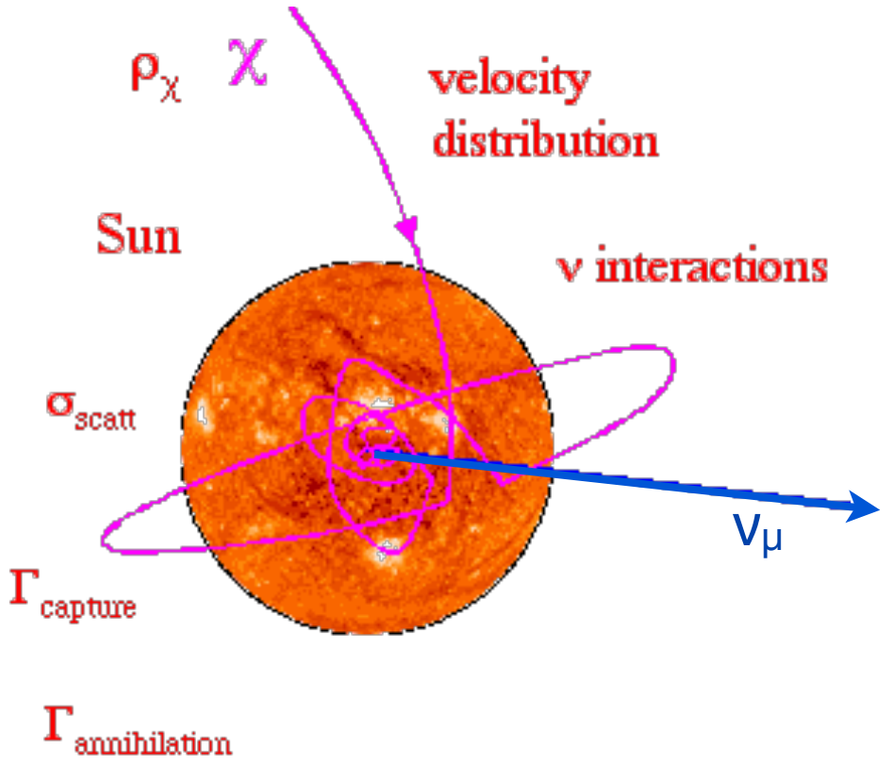
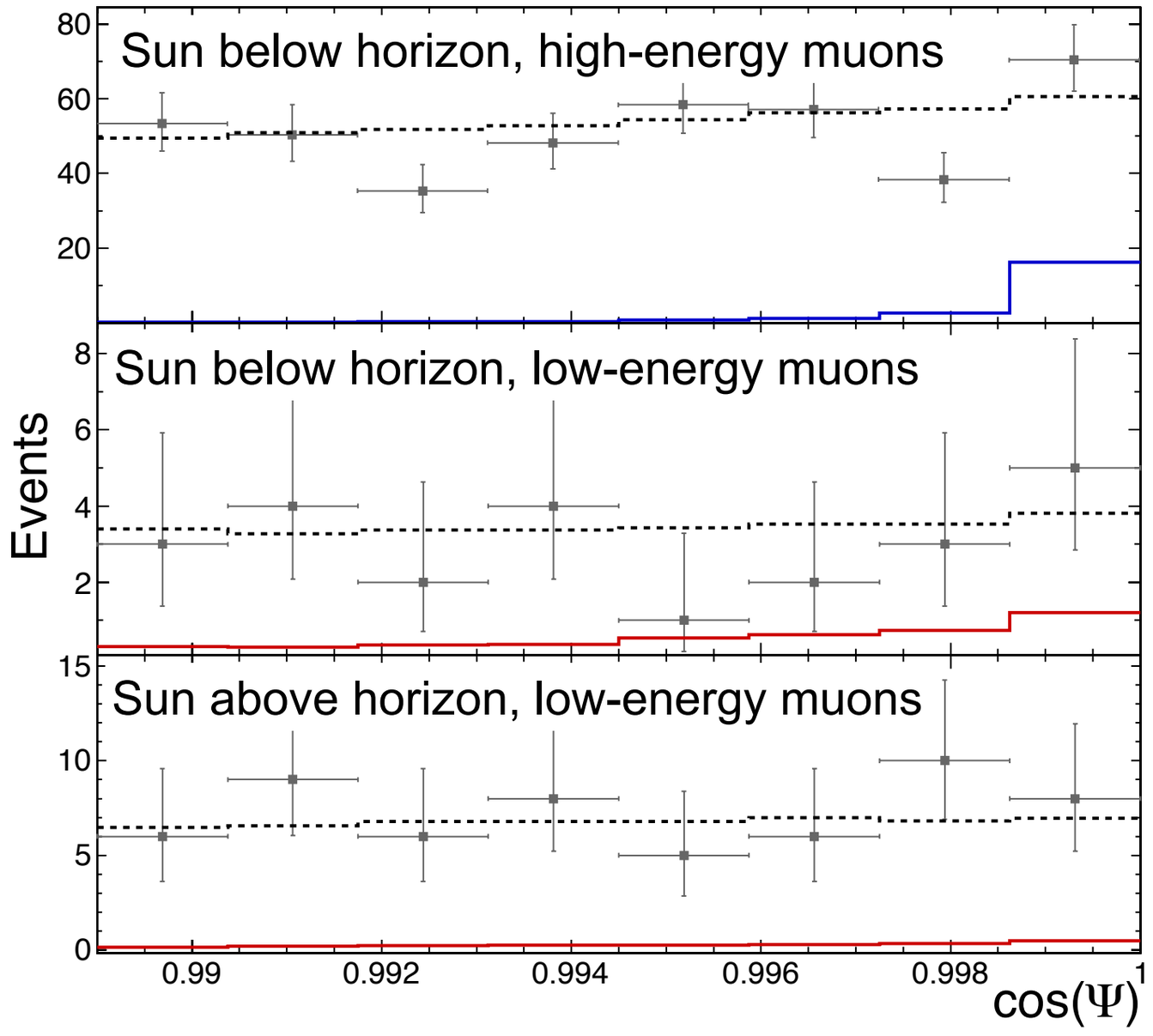
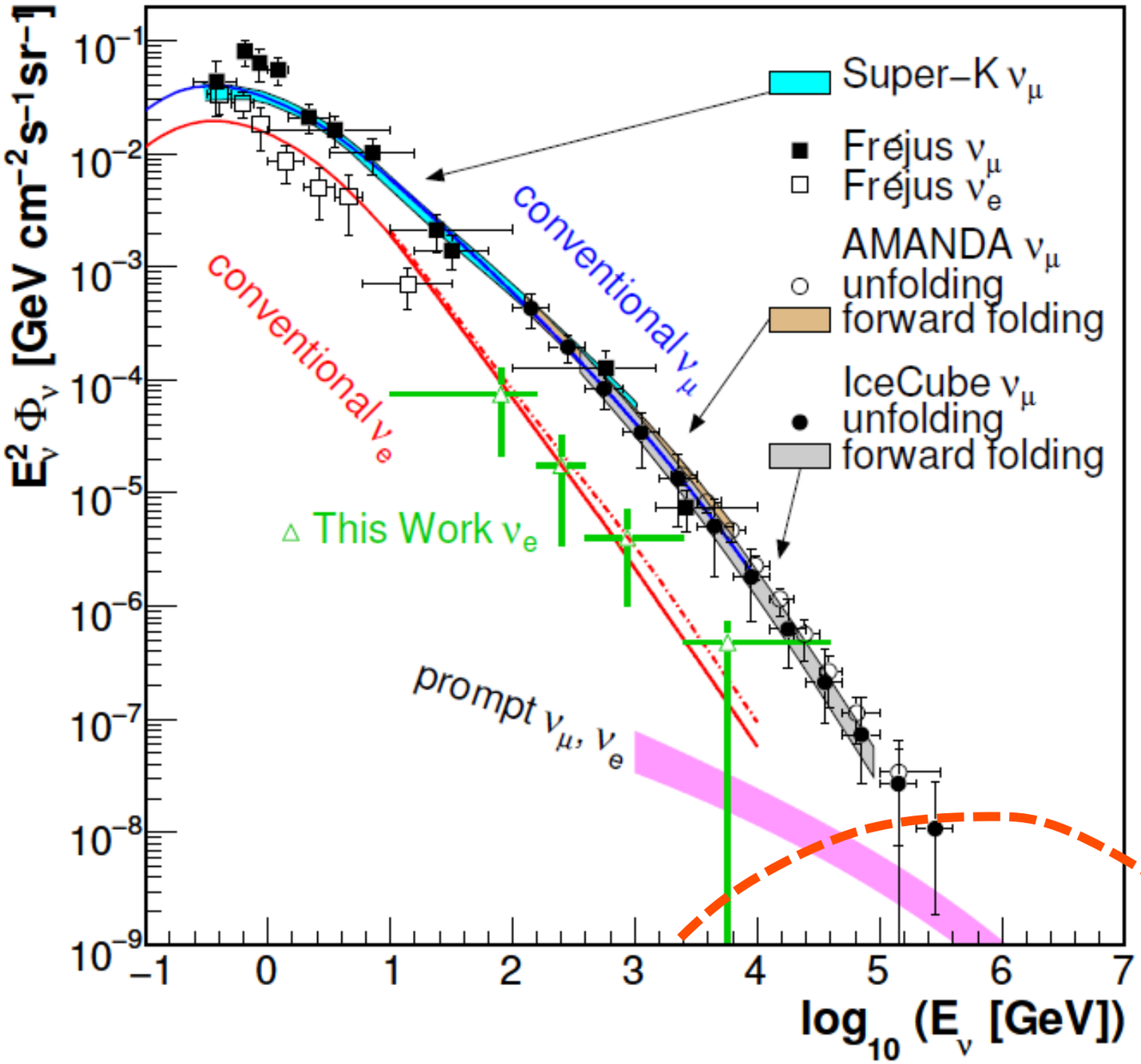


- DM particles **get captured** by scattering off atoms **in the Sun**.
- **Annihilation** of accumulated **WIMPs** produces neutrinos.
- In equilibrium: **Neutrino flux** depends only on **scattering cross section.**



← Offset from center of the sun.

Search for diffuse astrophysical neutrinos.



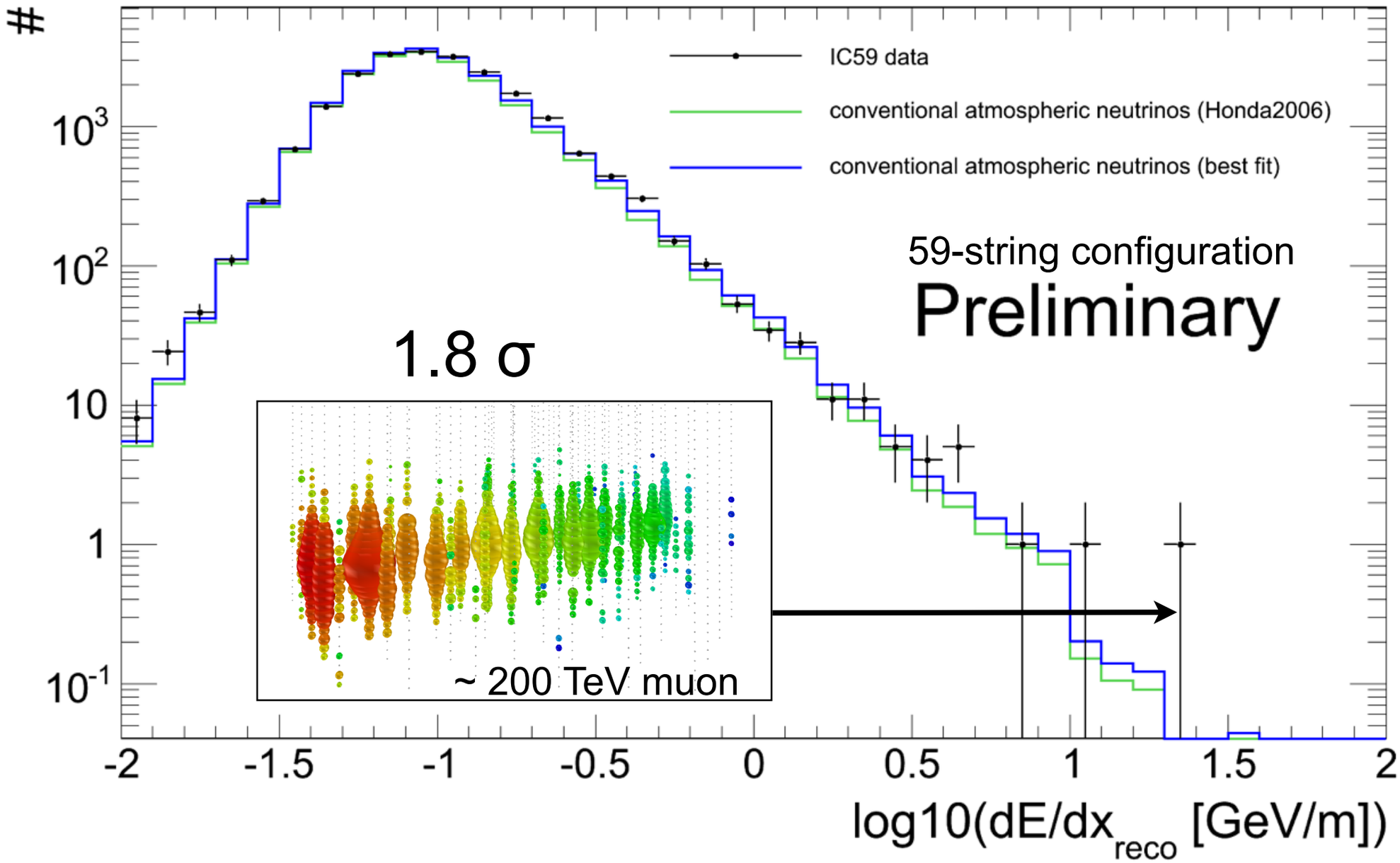
> Search for a **diffuse excess** of neutrinos over background from atmosphere at high energies.

- From unresolved neutrino sources
- From the interactions of CR with the extragalactic background light

> **Lower** atmospheric **background** for **shower-type** events (ν_e + NC ν_μ only)

extraterrestrial neutrinos ?

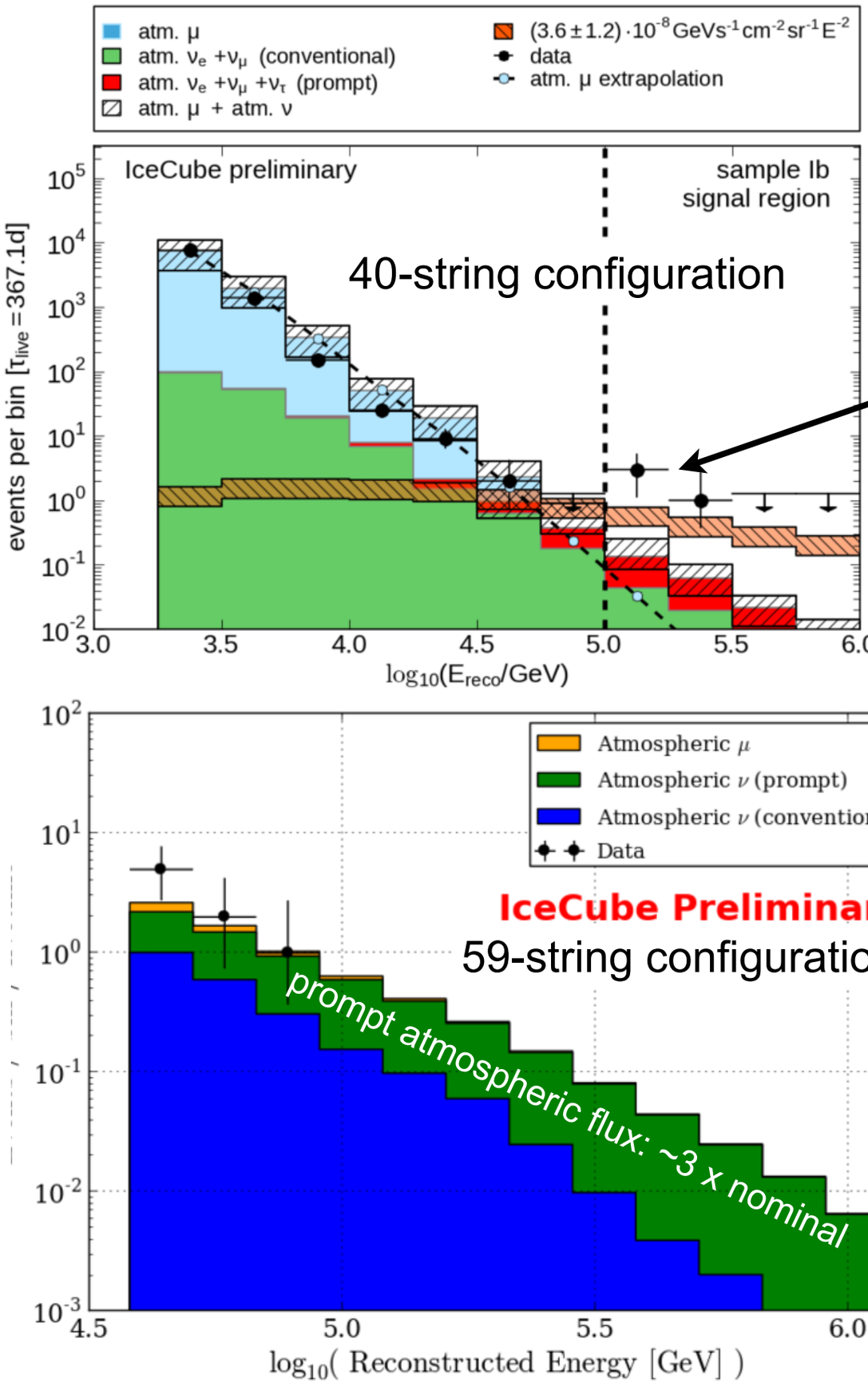
Search for diffuse astrophysical neutrinos: Construction phase.

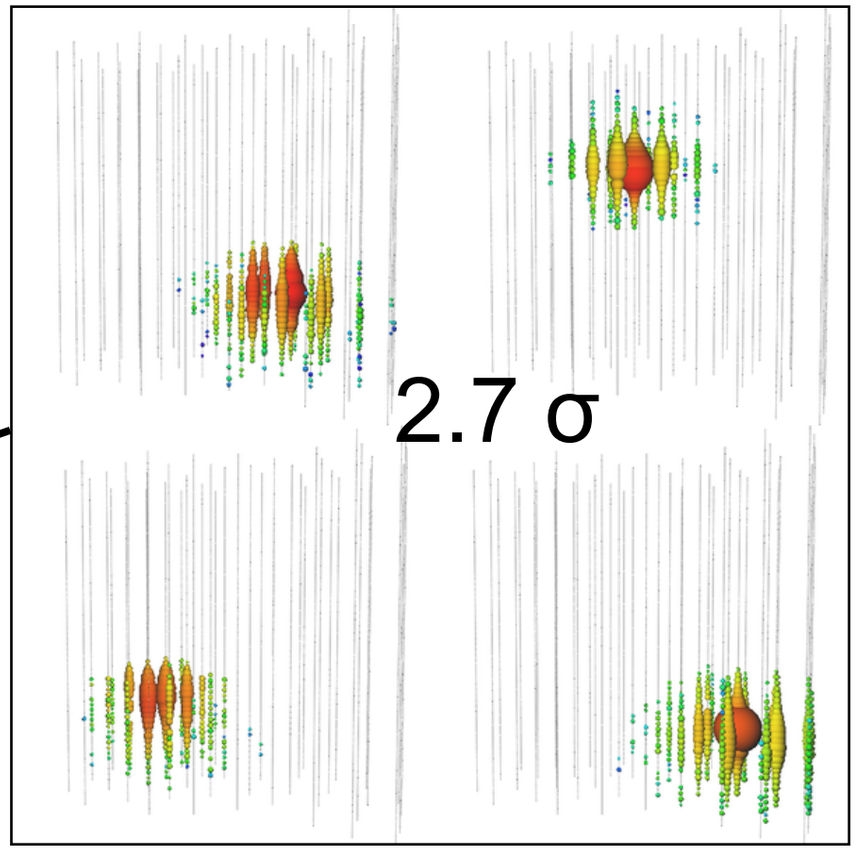


> Search for high-energy excess in the muon energy loss spectrum.

> Low-significance excess found in construction phase data.

Search for diffuse astrophysical neutrinos: Construction phase.



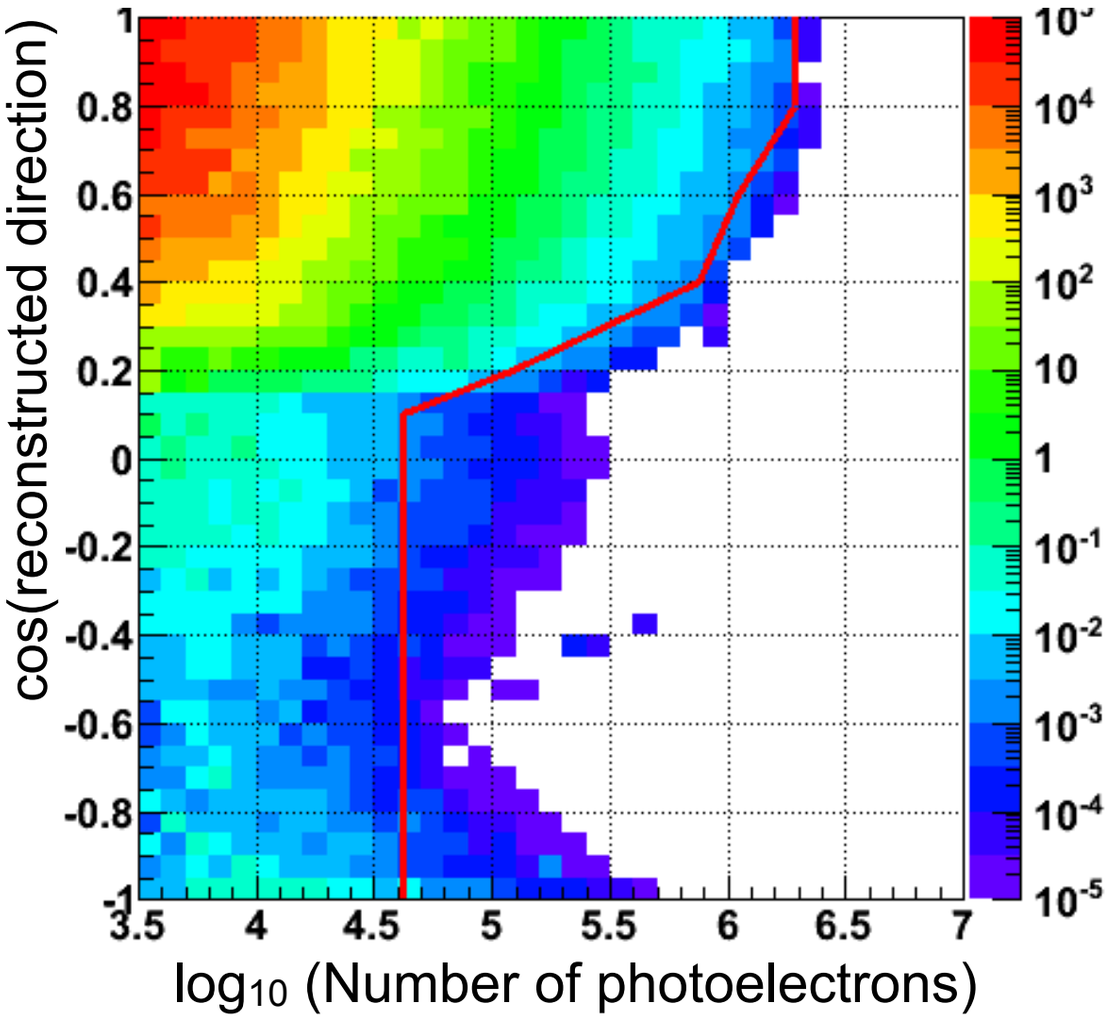


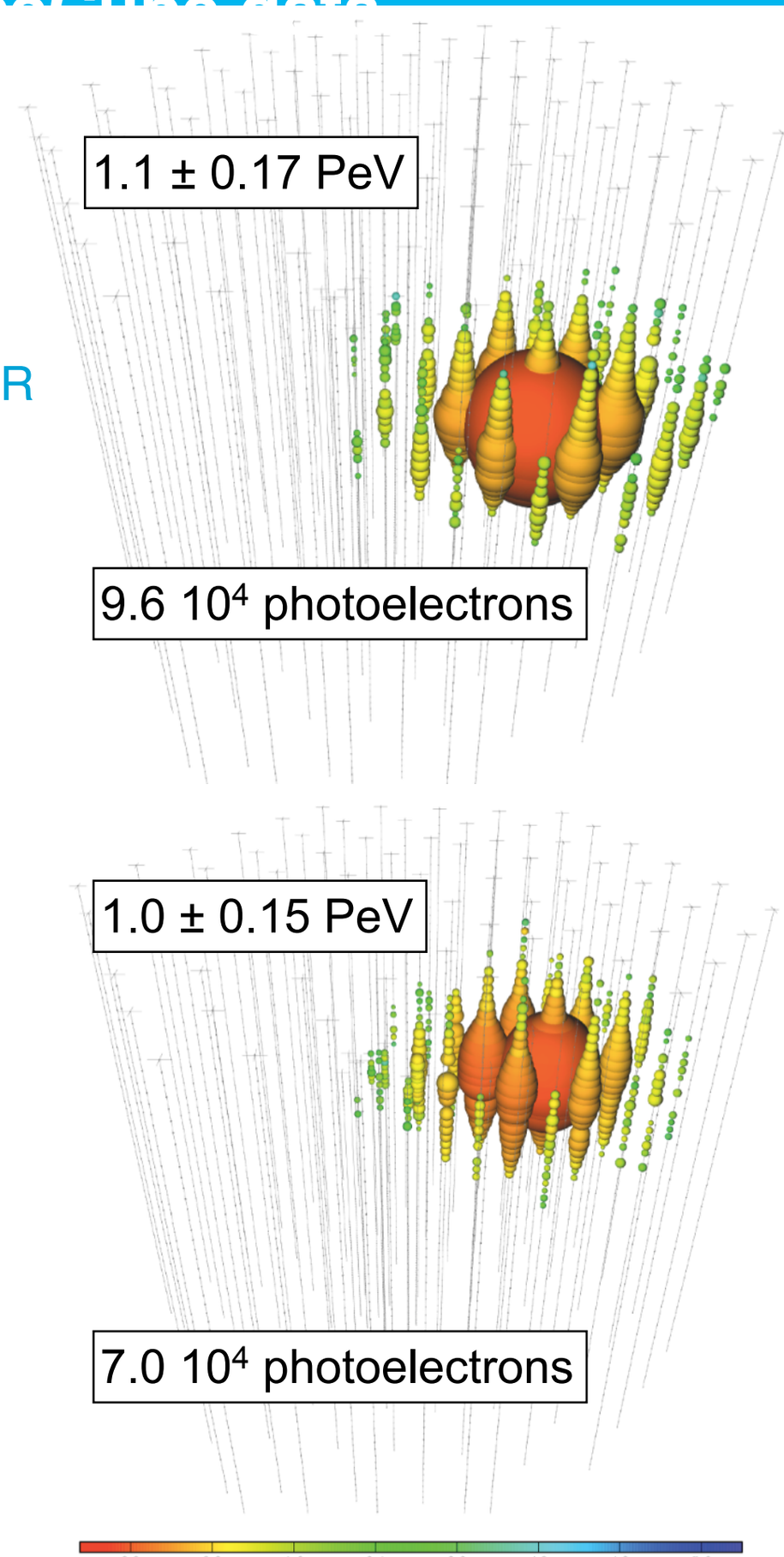
> **Excess events** observed in analysis of shower-like events.

- 4 events observed above 100 TeV in 40-string configuration.
- Excess of events in data from 59-string configuration (but compatible with background hypothesis within uncertainties)

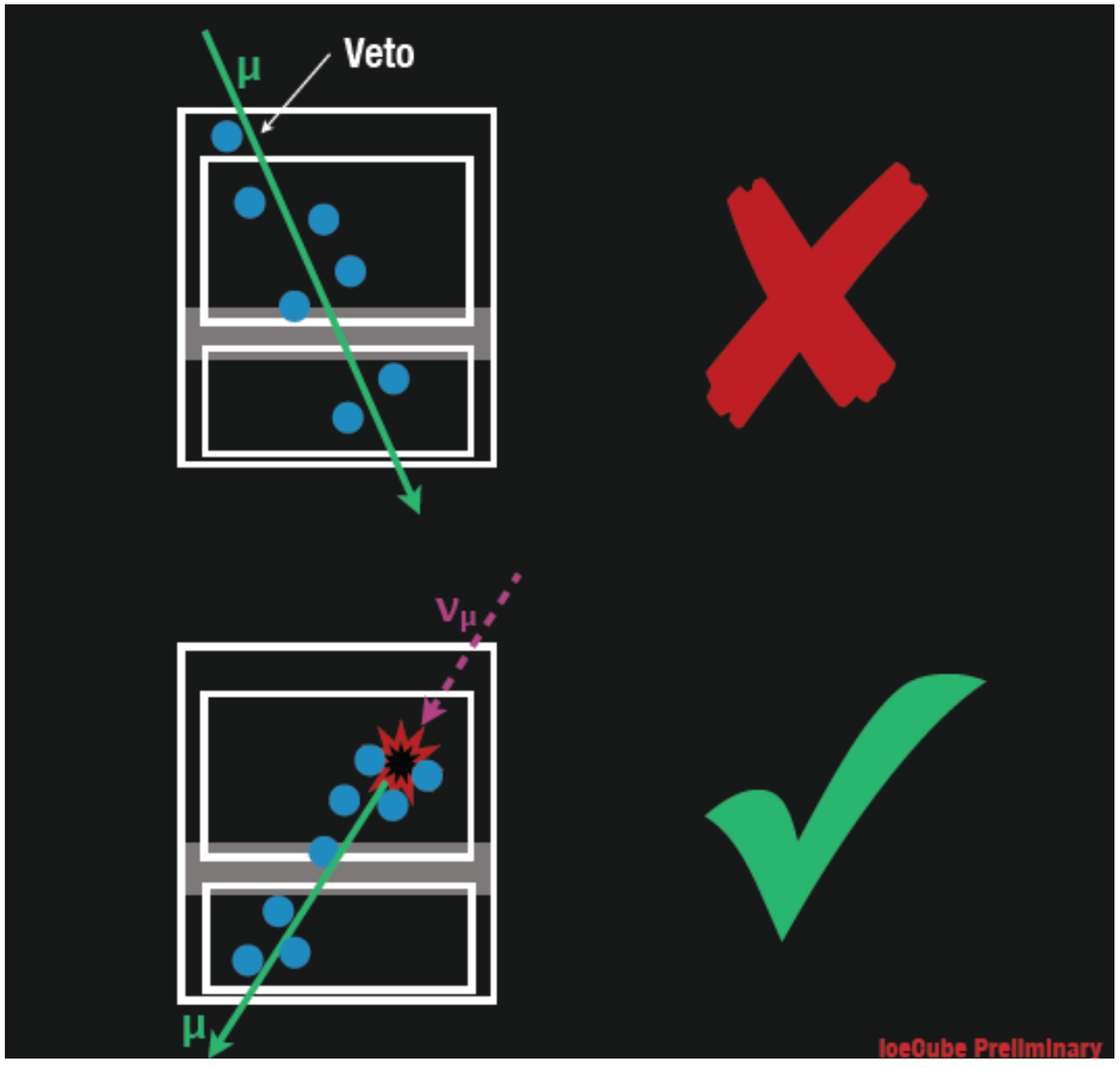
Search for bright events with 2 years of IceCube data

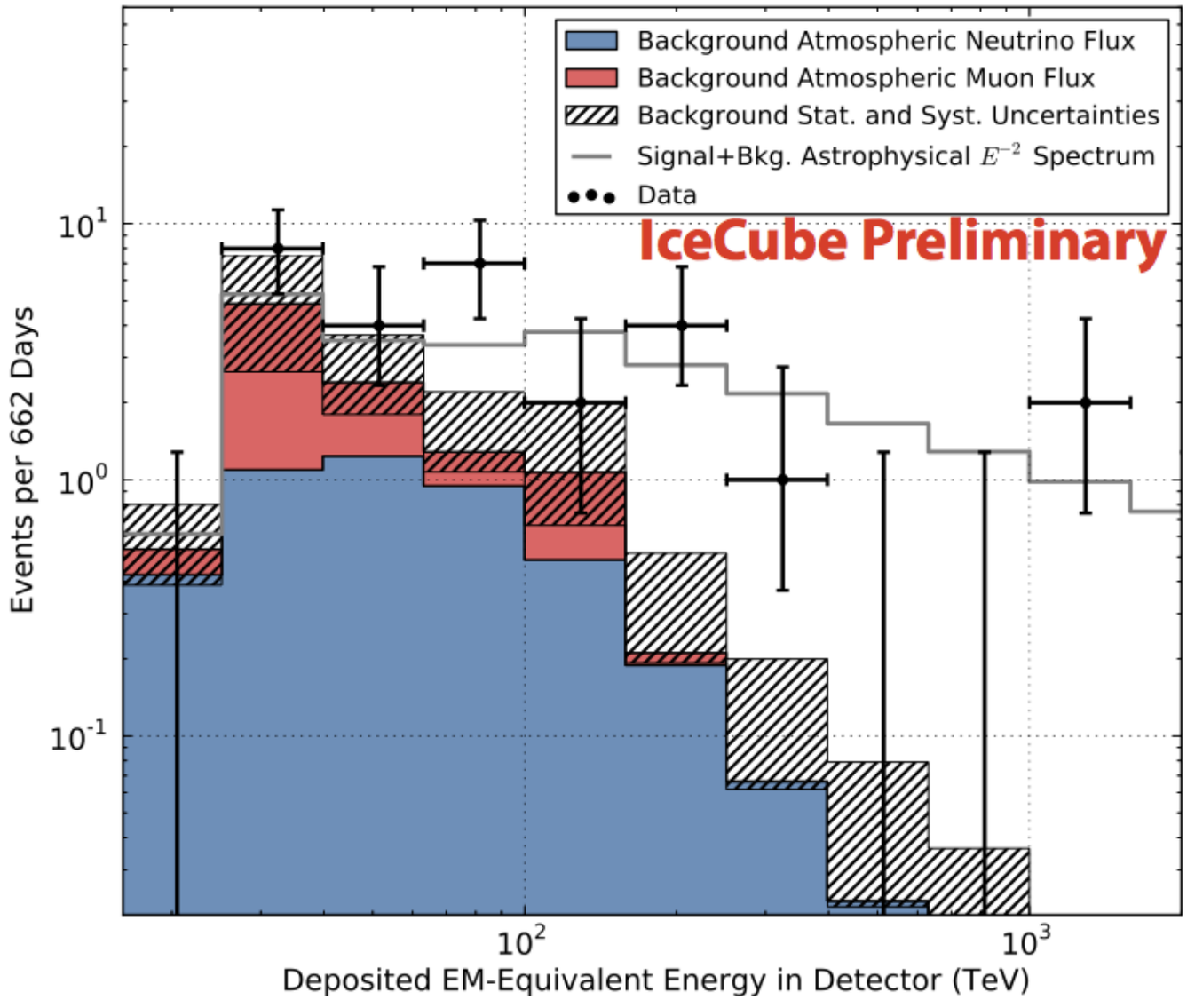
- 79-string and 86-string configurations.
- **Optimized** for **cosmogenic neutrinos** of EeV energies.
  Cosmogenic = produced in interactions of ultrahigh-energy CR with the CMB/background light.
- **2 events** just above threshold.
- **2.8σ excess** above expected atmospheric-ν flux.





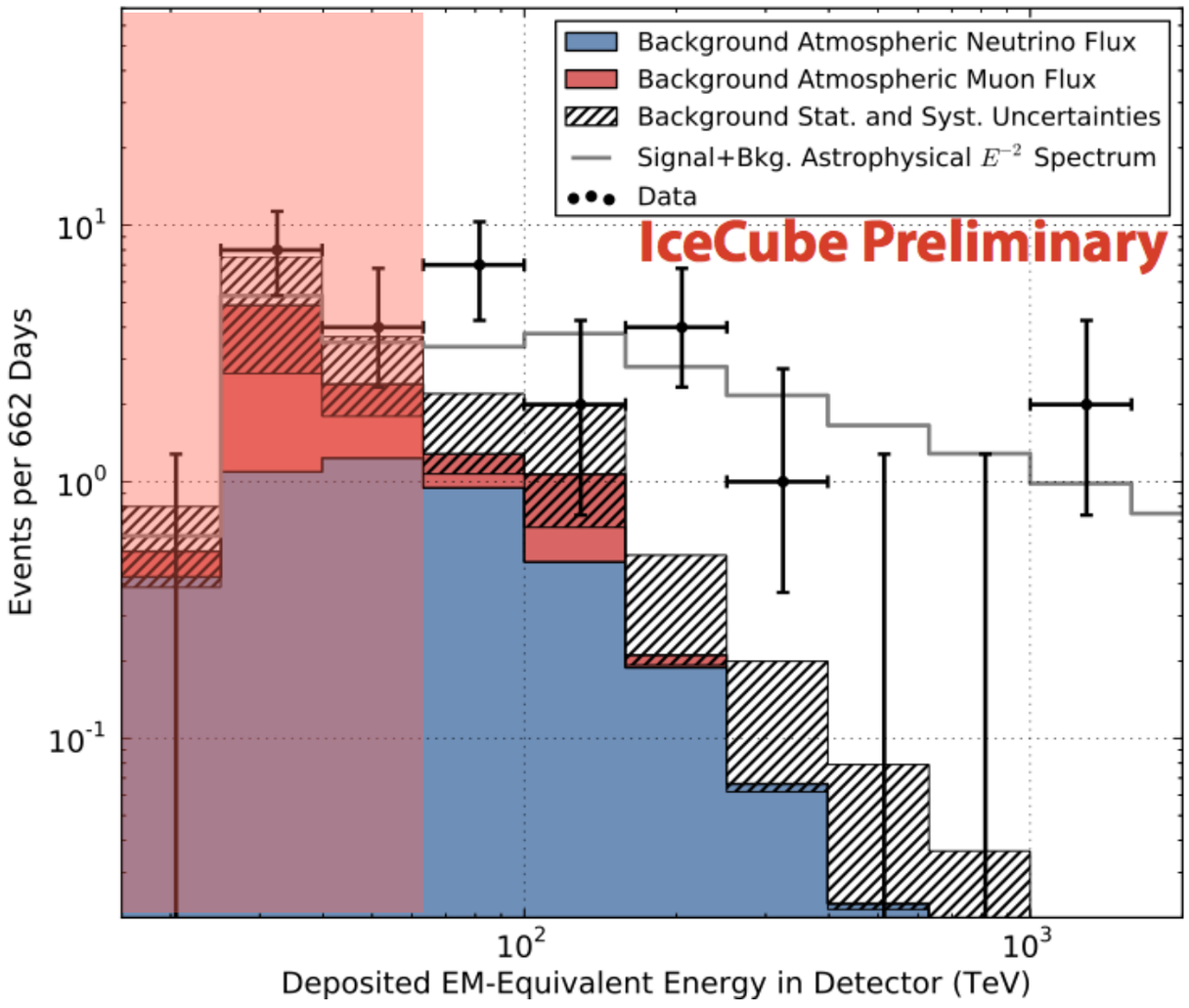
Search for a diffuse astrophysical flux.





- **Extension** of previous search to **lower energies** (~ 30 TeV energy threshold)
- **New strategy** to reject CR background.
- **28 events** found in 2010-2012 dataset.
- **4.1σ excess** over expected backgrounds from atmospheric μ / ν

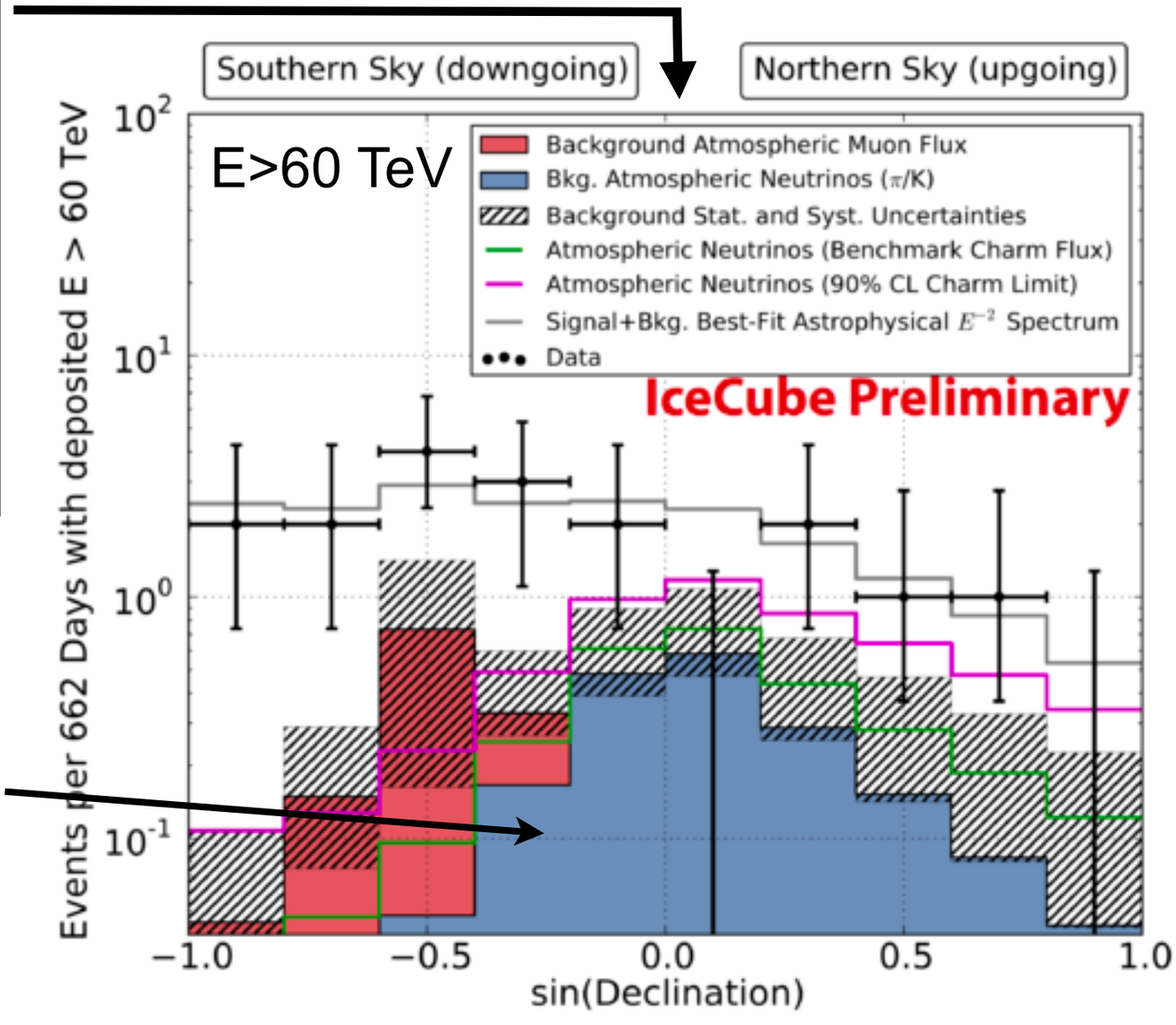
Spectral and angular distribution.



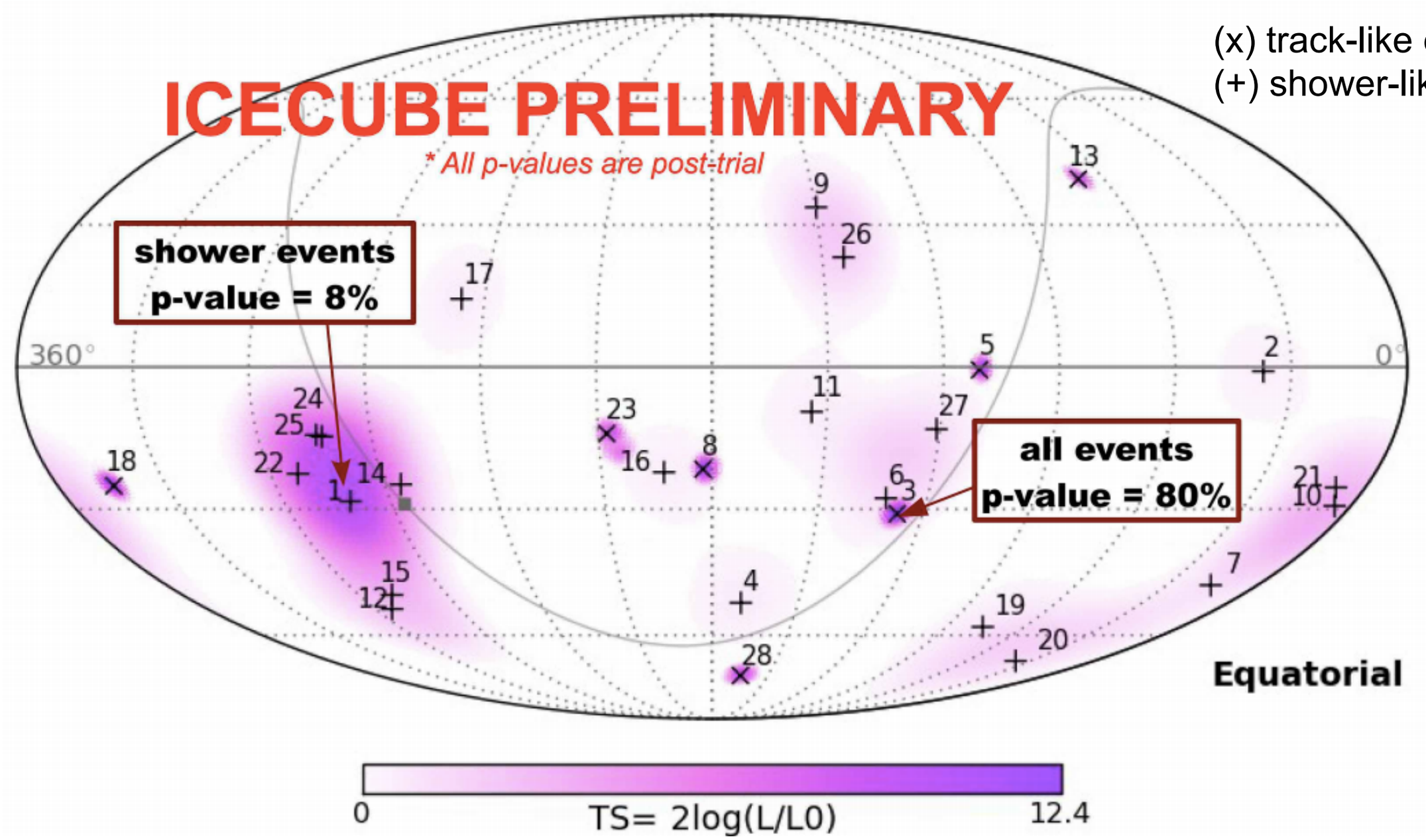
> **Spectrum** and **zenith distribution** compatible with an astrophysical flux with a power-law spectrum ($\Phi \sim E^{-2}$) between 60 TeV and 2 PeV.

Atmospheric neutrinos on southern hemisphere suppressed by “self-veto”:

- p + air → X + ν_μ + ν_e + ... + μ
- high-energy μ from shower triggers veto

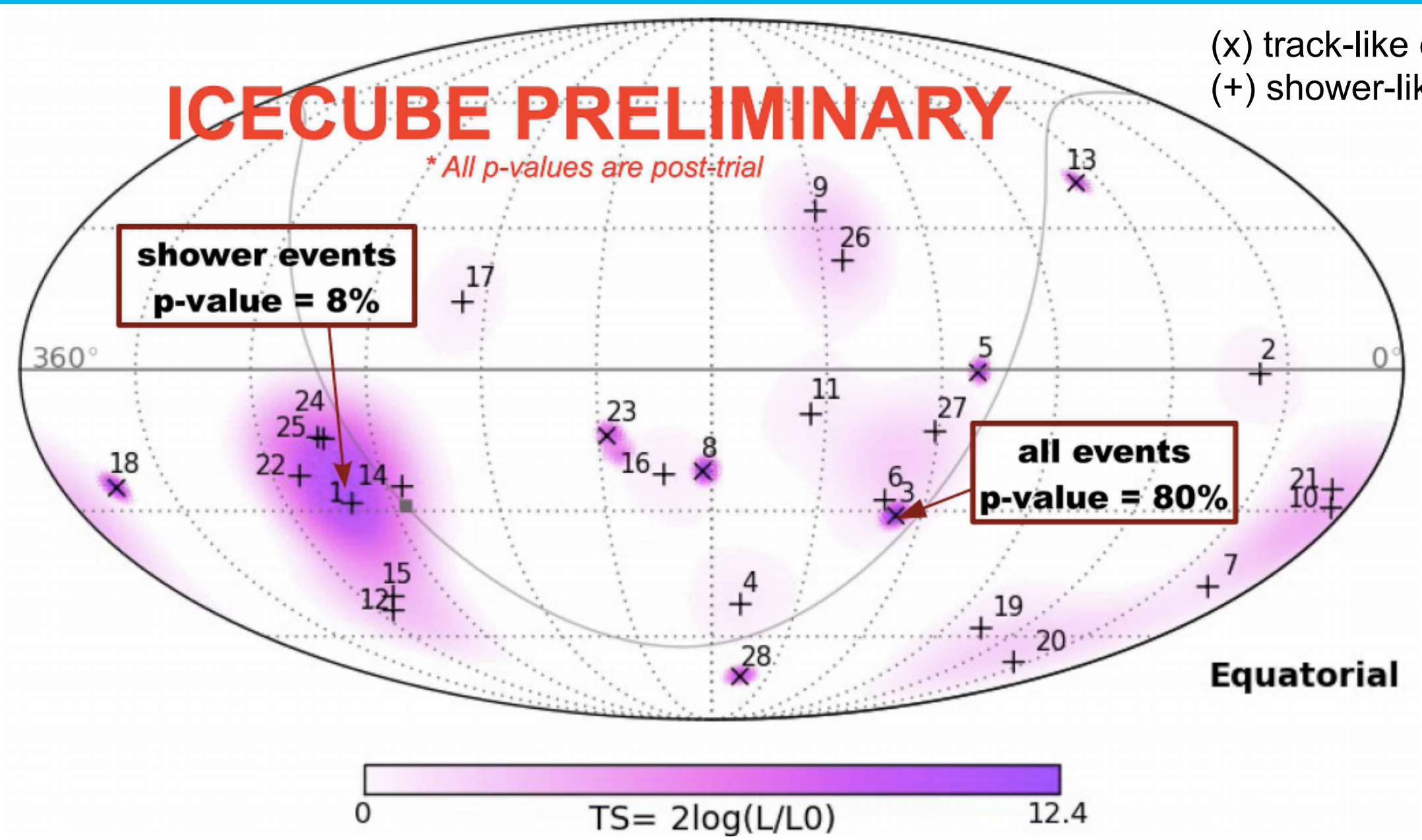


Distribution of high-energy neutrinos on the sky.



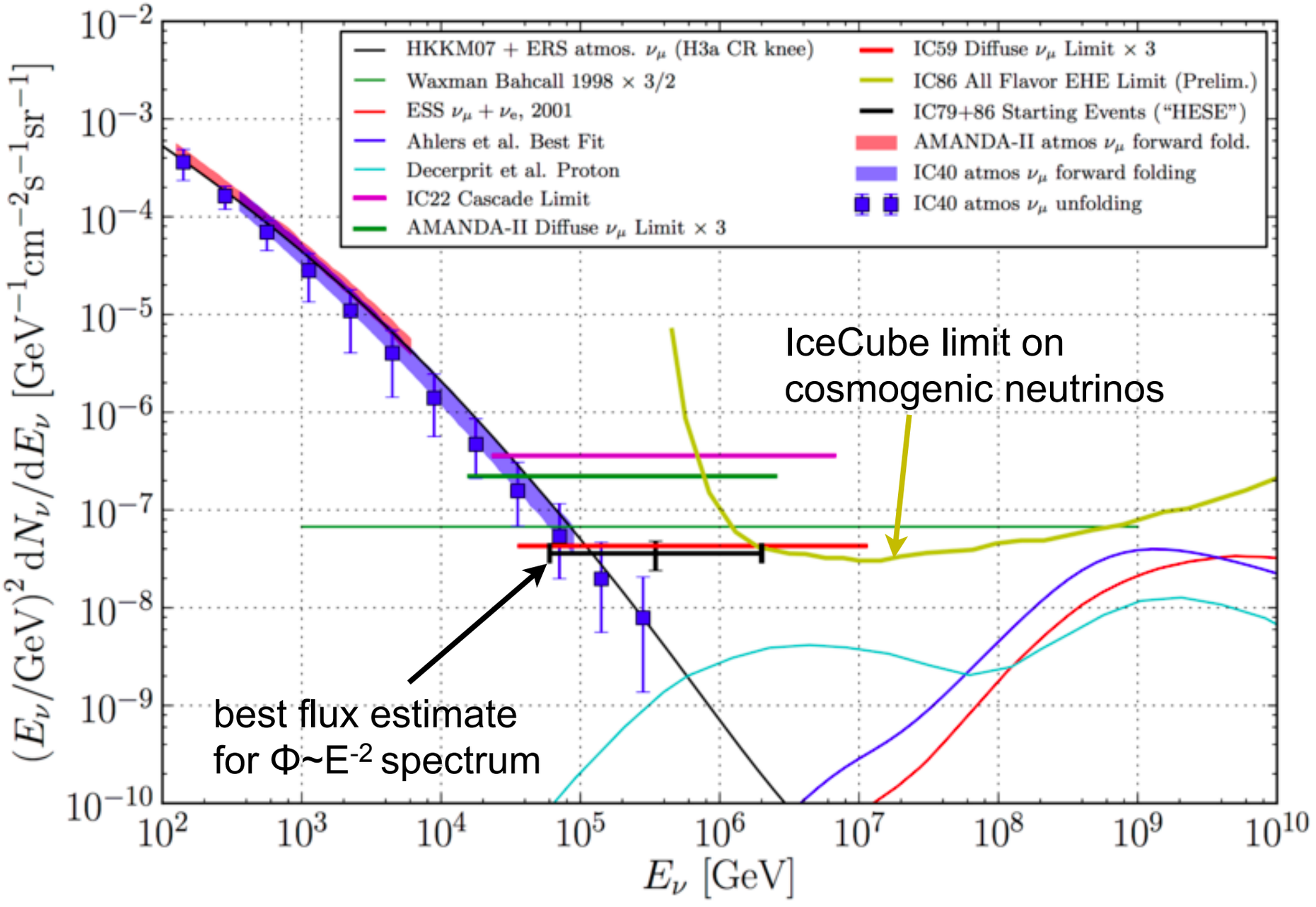
- **21 shower-like** events, 7 track-like events
- Dominance of shower-like events expected from astrophysical neutrinos due to flavor ratio of $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$

Distribution of high-energy neutrinos on the sky.



- **Event distribution** compatible with expectations from background + isotropic astrophysical flux.
- **No significant correlation** in space/time with GRBs found.

Searches for diffuse astrophysical and cosmogenic neutrinos.



> Observed excess is **too low in energy** to be of **cosmogenic** origin.

> IceCube starts to probe the phase space of cosmogenic neutrino models.

A global spectral fit to all IceCube data.

Hypothesis:

$\phi_{\text{astro}} \sim E^{-2} \cdot \exp(E/E_{\text{cut}})$

Goodness-of-fit:

7.8 %

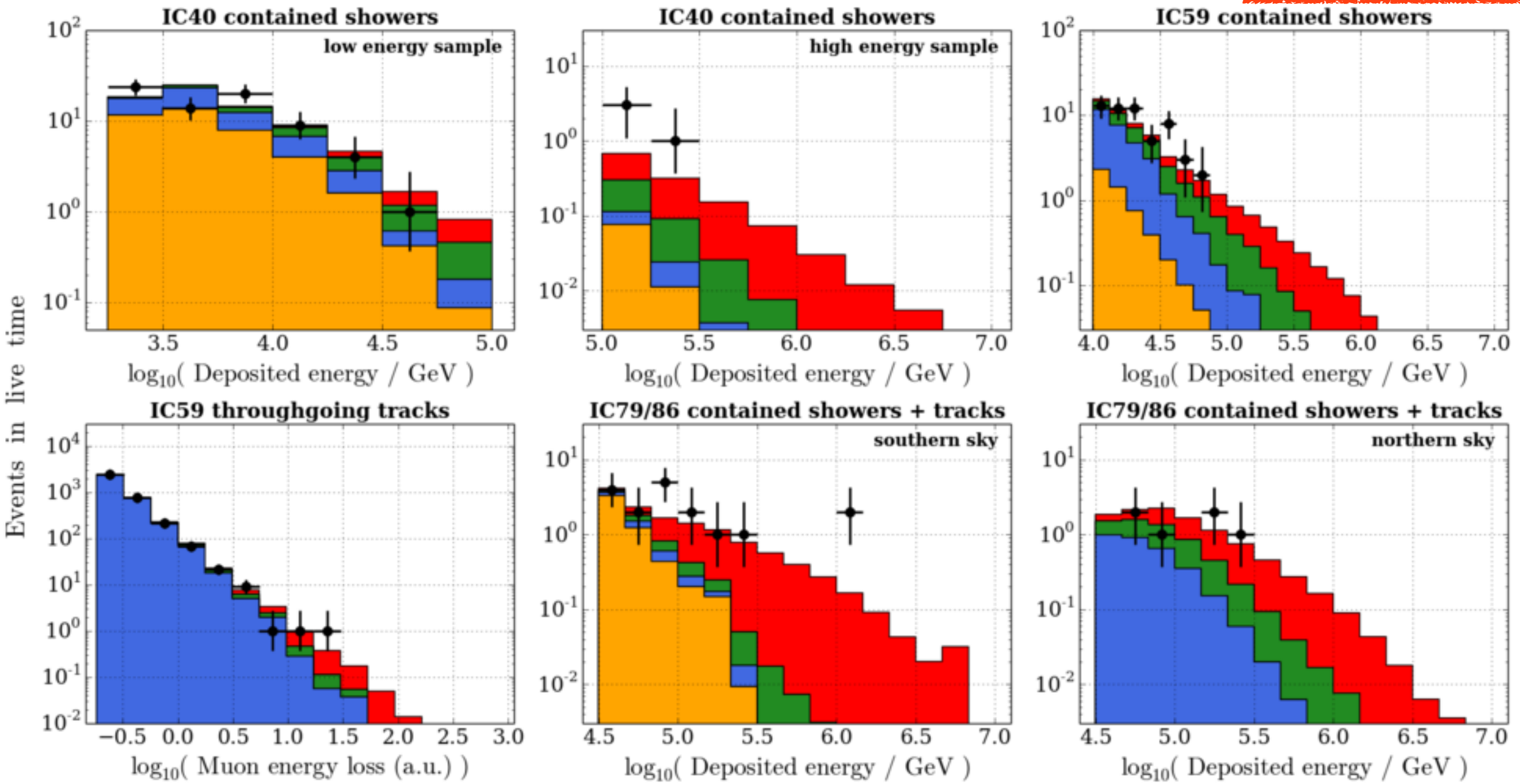
IceCube Preliminary

Atmospheric ν (conv.)
Atmospheric ν (prompt)
Atmospheric μ
Astrophysical ν
Data

$\phi_{\text{prompt}} = (2.8^{+2.0}_{-2.0}) \cdot$ [Enberg + Gaisser H3a]

$E^2 \phi_{\text{astro}} = (1.0^{+0.8}_{-0.5}) \cdot 10^{-8}$ GeV s^{-1} sr^{-1} cm^{-2}

$E_{\text{cut}} = (1.8^{+5.0}_{-1.0})$ PEV



> **Hard spectrum** with cutoff: $\Phi \sim E^{-2} \exp(-E/E_{\text{cut}})$

A global spectral fit to all IceCube data.

Hypothesis:

$\phi_{\text{astro}} \sim E^{-\gamma}$

Goodness-of-fit:

10.0 %

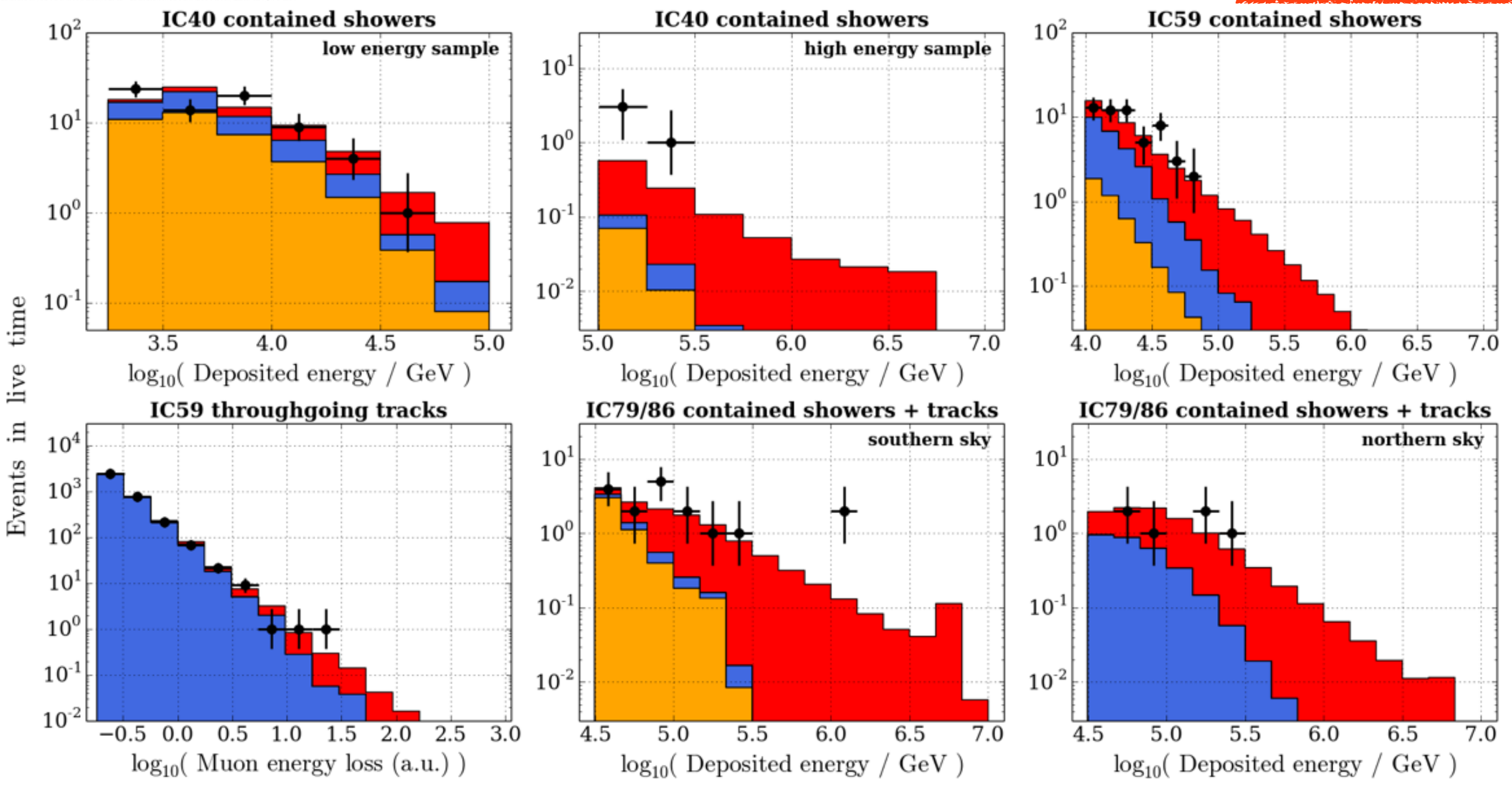
IceCube Preliminary

Atmospheric ν (conv.)
Atmospheric ν (prompt)
Atmospheric μ
Astrophysical ν
Data

$$\phi_{\text{prompt}} = (0^{+1.6}_{-0.0}) \cdot [\text{Enberg} + \text{Gaisser H3a}]$$

$$E^{2.7}\,\phi_{\text{astro}} = (6.8^{+1.8}_{-1.8}) \cdot 10^{-5}\,\text{GeV}^{1.7}\ \text{s}^{-1}\ \text{sr}^{-1}\ \text{cm}^{-2}$$

$$\gamma_{\text{astro}} = (2.7^{+0.2}_{-0.2})$$



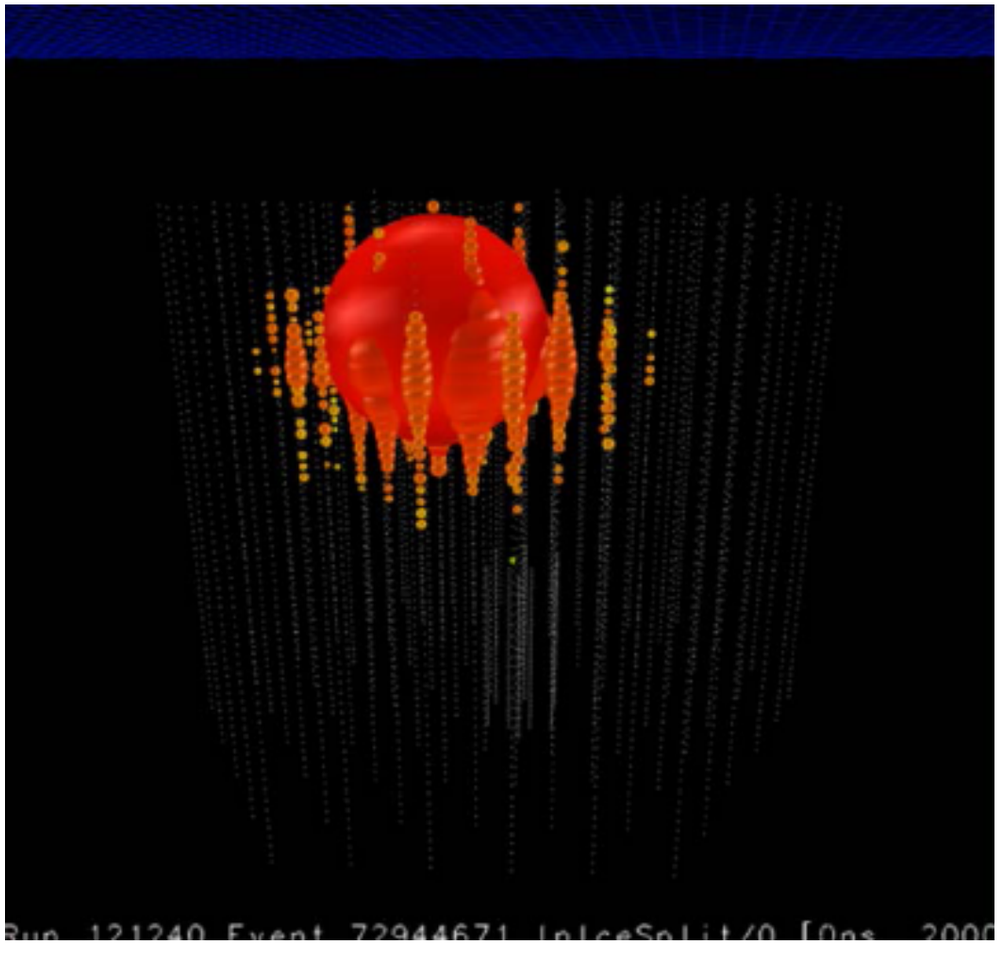
> **Pure power-law** with unknown index: $\Phi \sim E^{-\gamma}$

More results expected soon.

> Analysis of **2012/2013** IceCube **data** (run period from May 2012 - Apr 2013).

> **Better constraints** on atmospheric neutrino fluxes from **low-energy** contained/semi-contained events.

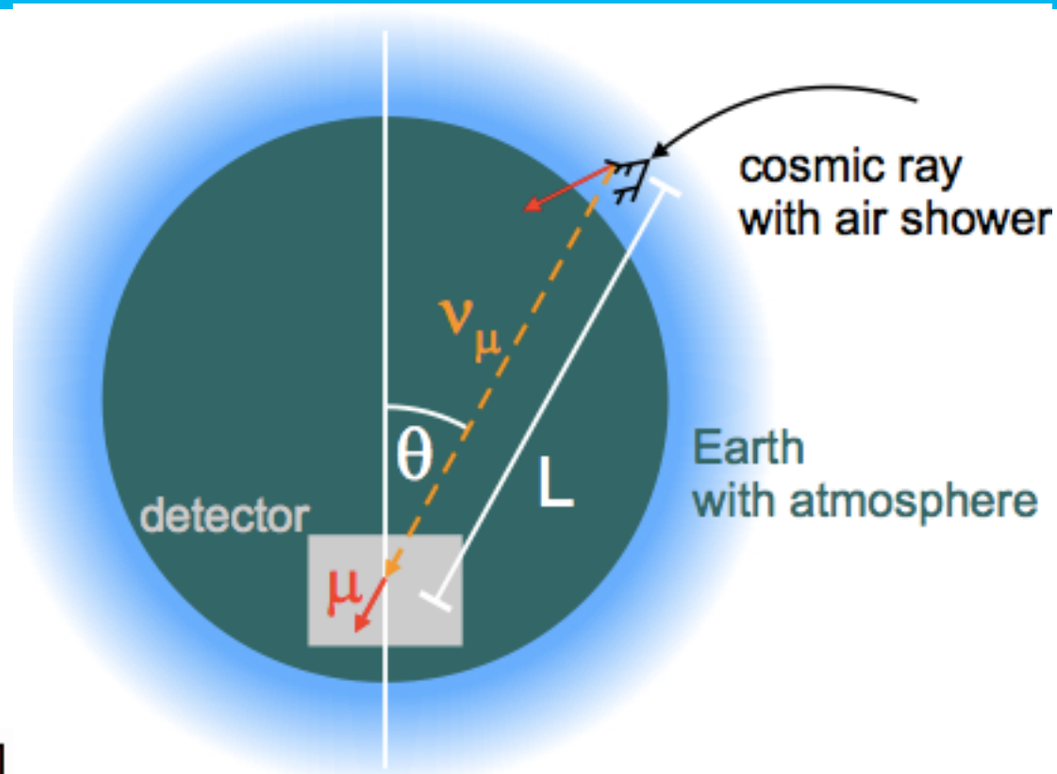
> Search for **excess events** in the **dE/dx spectrum** of through-going tracks with the completed IceCube observatory.

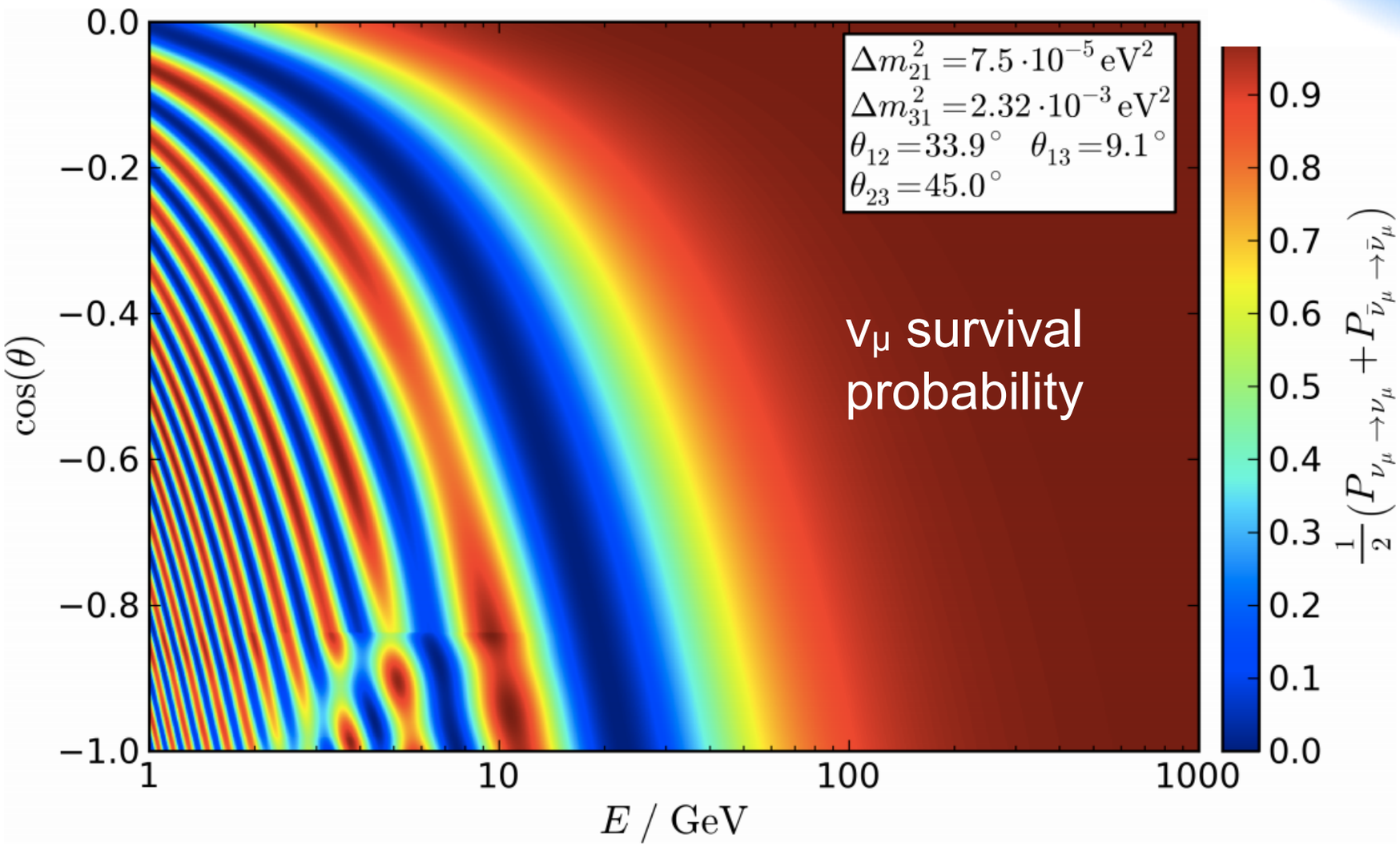


Another PeV-class neutrino in pre-scaled 2012/2013 data sample used for analysis development (10% of available data).

Studies of neutrino properties with IceCube.

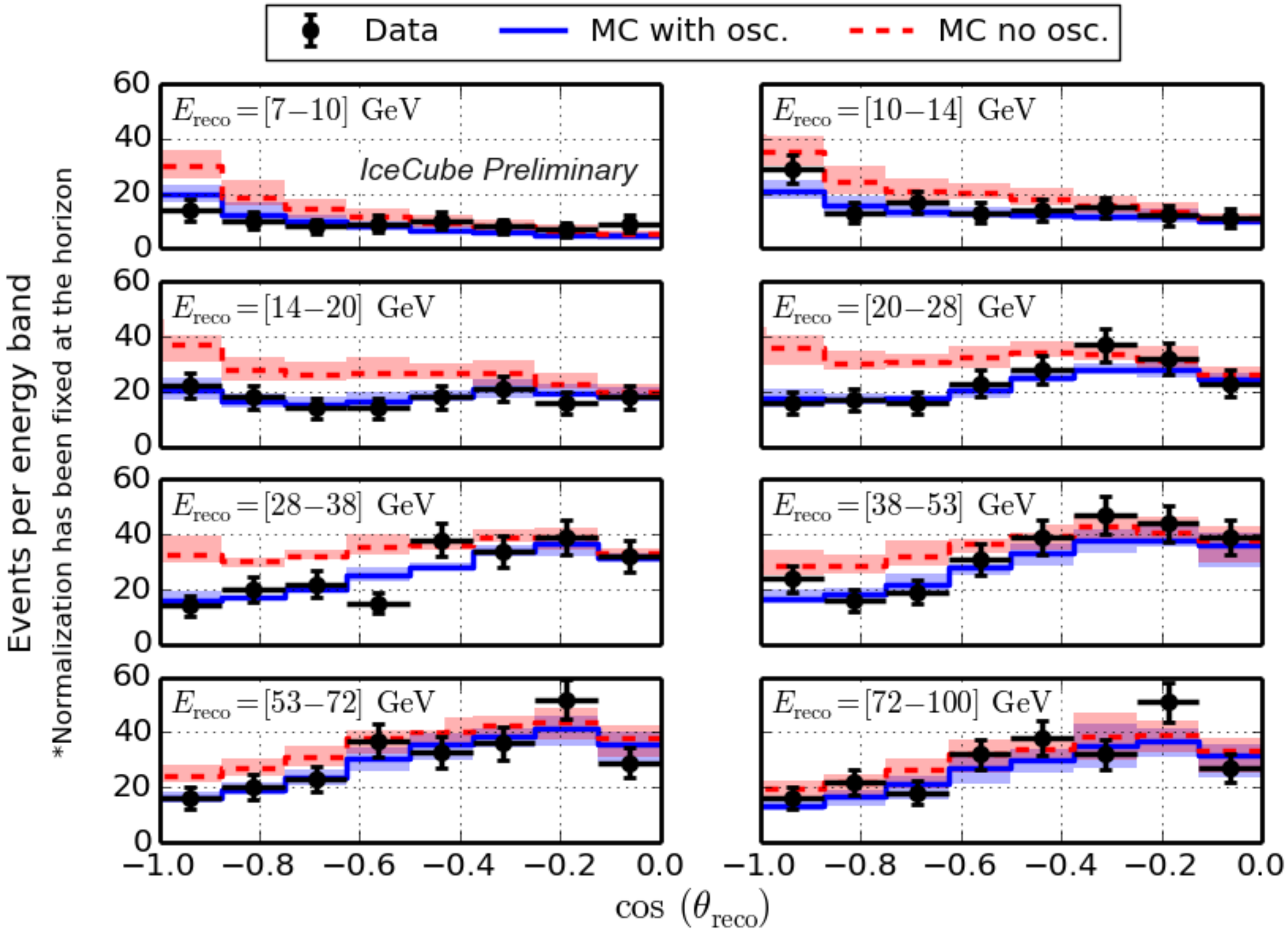
- Measurement of Δm^2_{23} and $\sin^2(2\theta_{23})$ using **DeepCore** sub-detector.
- **Zenith angle** of atmospheric neutrinos reflects different **baselines L**.
- For vertical events: ν_μ **survival probability** minimum **~ 25 GeV**.





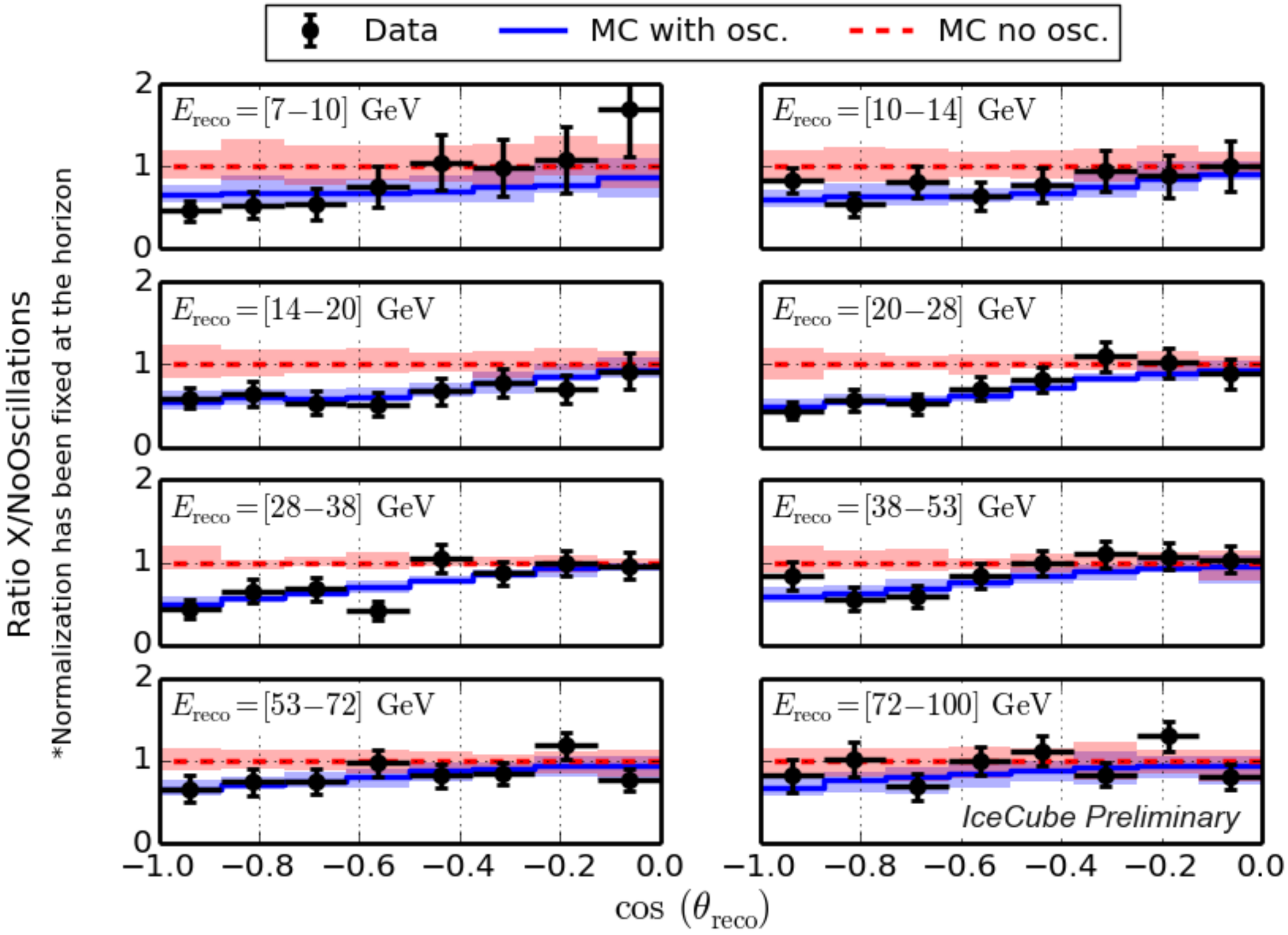
- High-energy events can be used to **control systematics**.

Studies of neutrino properties with IceCube.



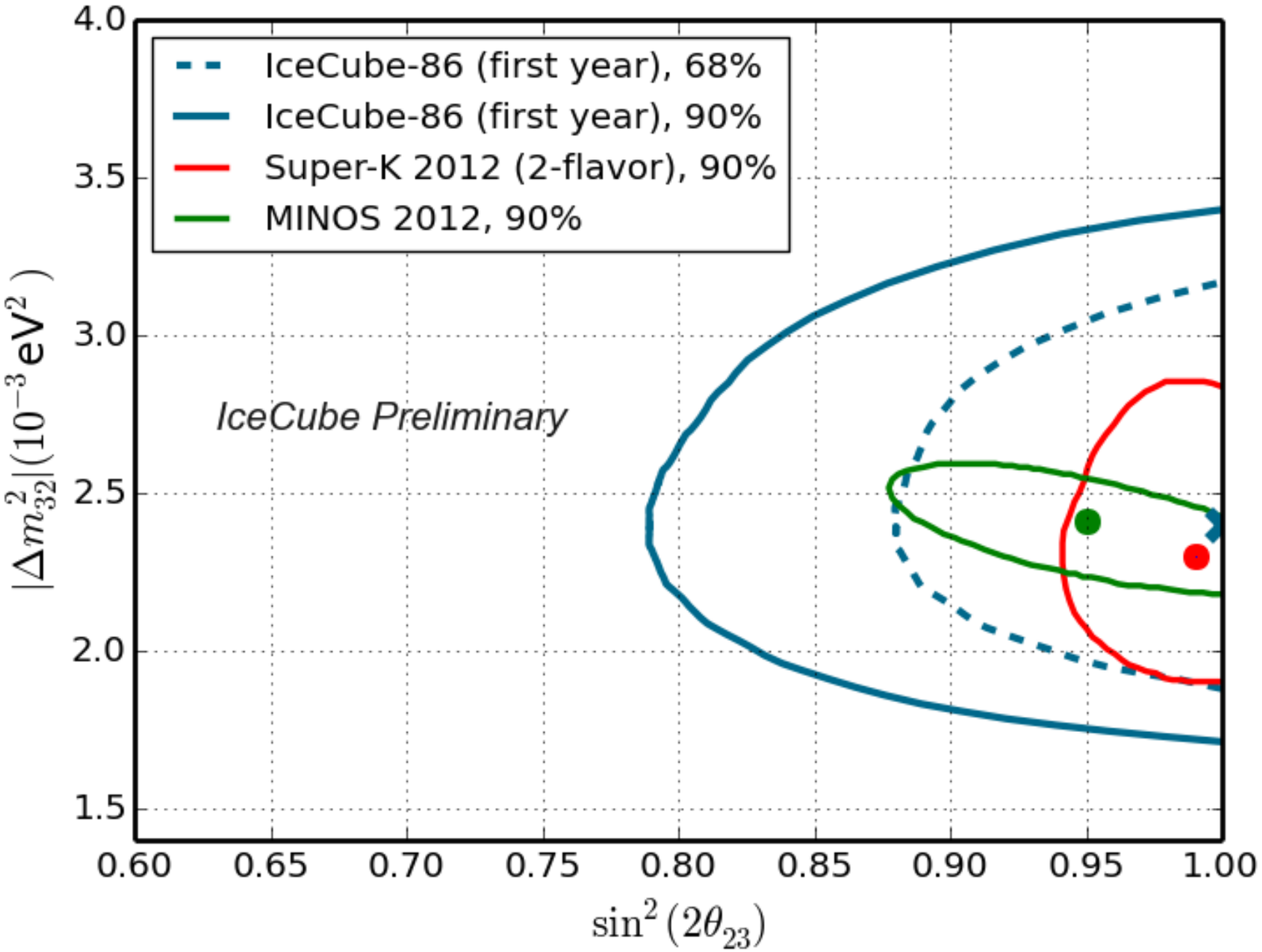
> Analysis performed using **one year** of available full **IceCube** data.

Studies of neutrino properties with IceCube.



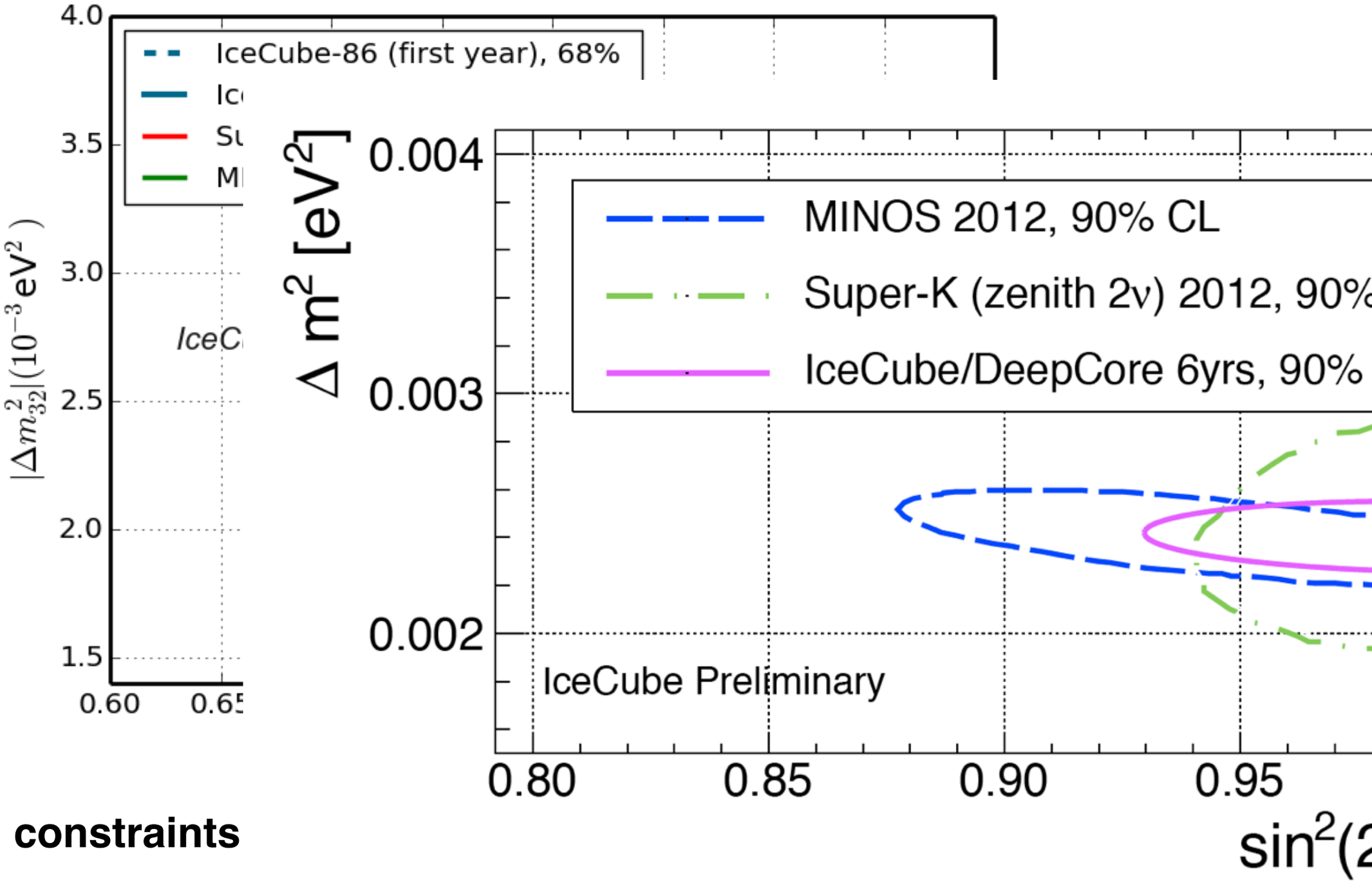
> Analysis performed using **one year** of available full **IceCube** data.

Constraints on oscillation parameters.



- **Promising constraints** on oscillation parameters from analysis.
- Uncertainty band **dominated by statistics** → Competitive constraints from multi-year dataset.

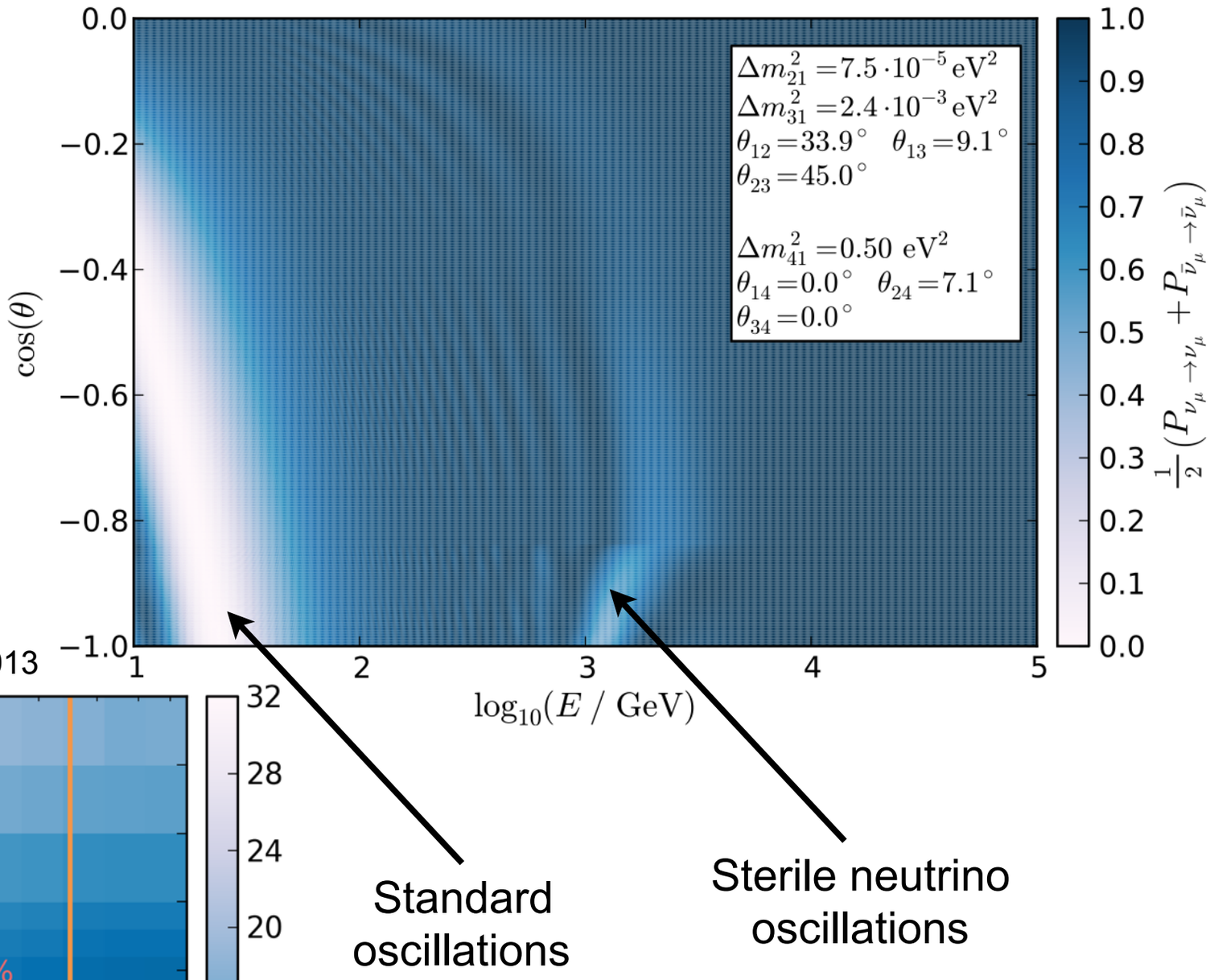
Constraints on oscillation parameters.



- **Promising constraints**
- Uncertainty band **domir** year dataset.

Sensitivity to sterile neutrinos.

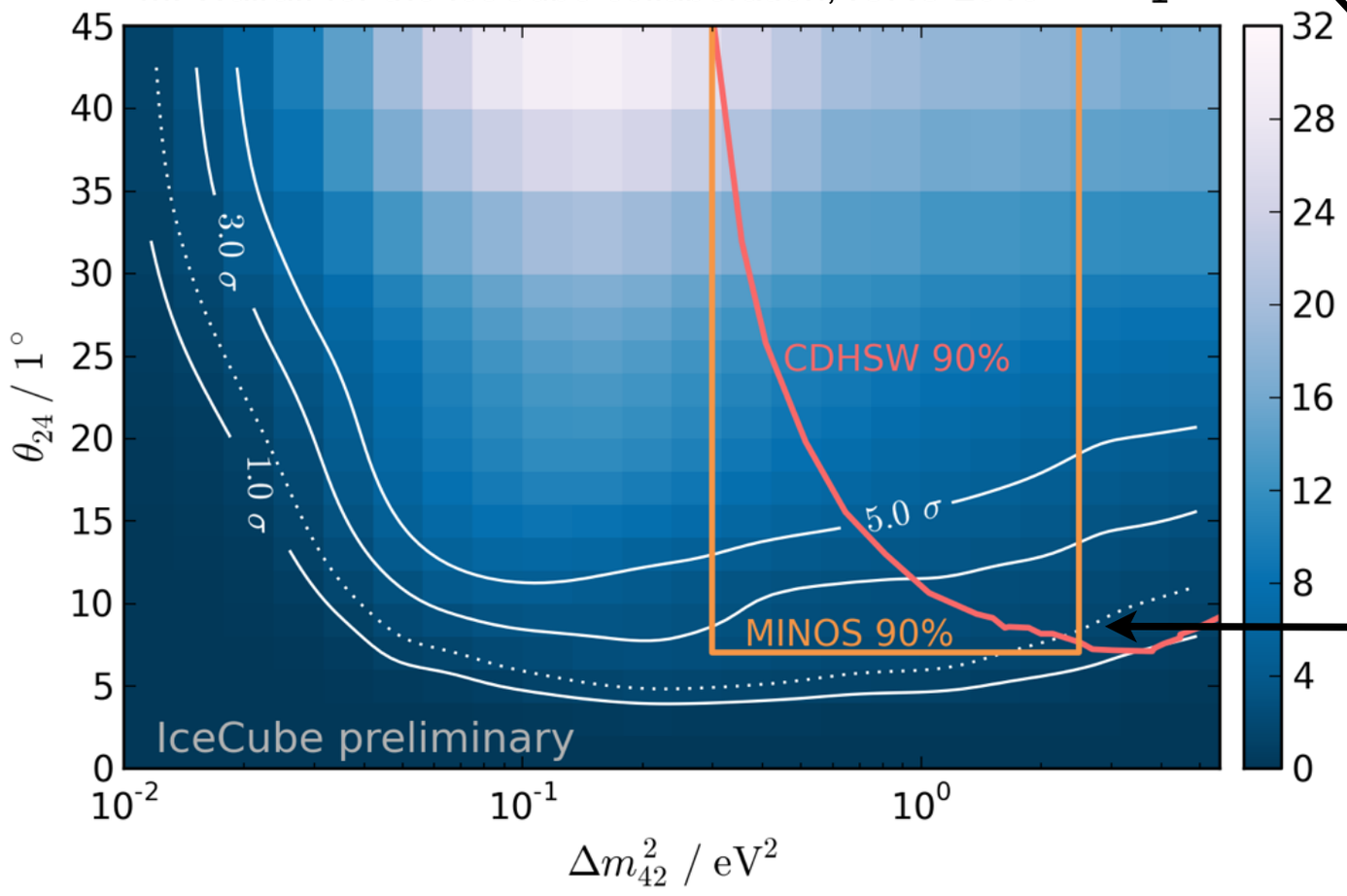
- IceCube is sensitive to **O(eV) sterile neutrinos.**
- Search for **oscillation** patterns of **TeV neutrinos.**
- **Competitive limits** expected from full IceCube array.



Standard oscillations

Sterile neutrino oscillations

M. Walraff for the IceCube collaboration, ICRC 2013



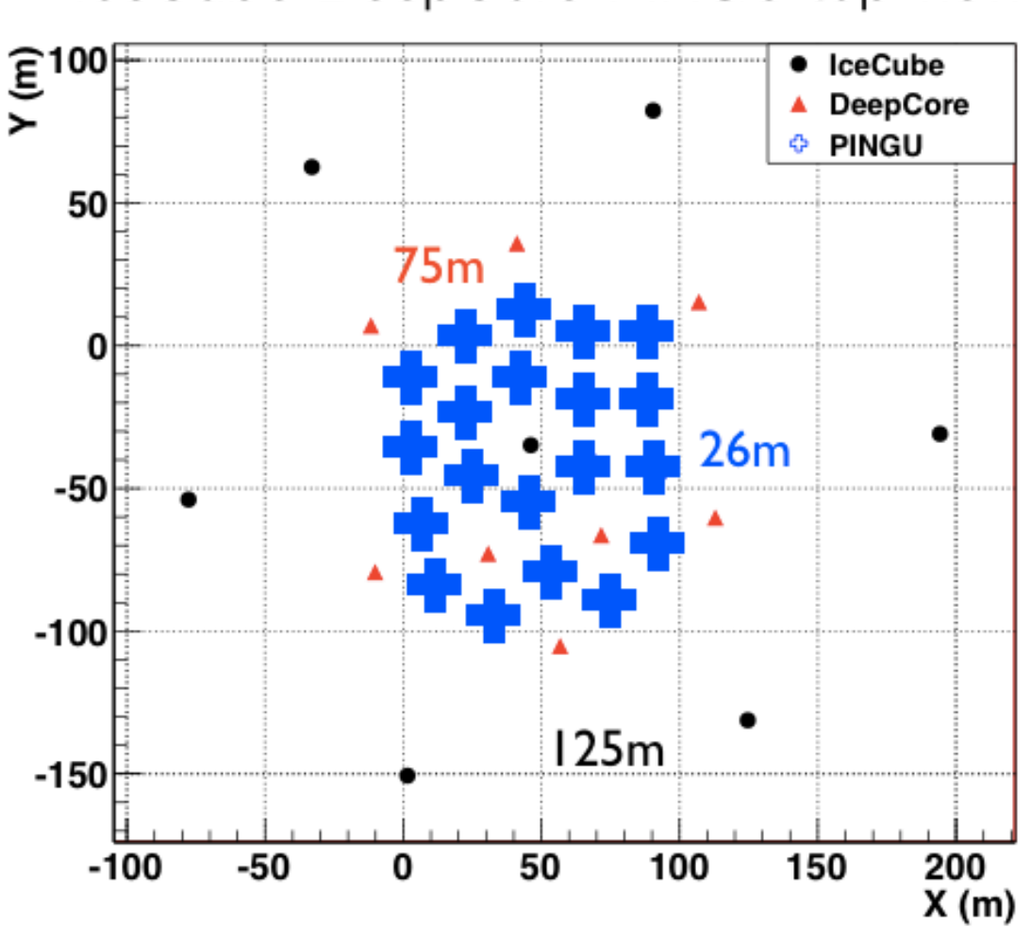
IceCube 5-year 90% exclusion sensitivity

Beyond IceCube.

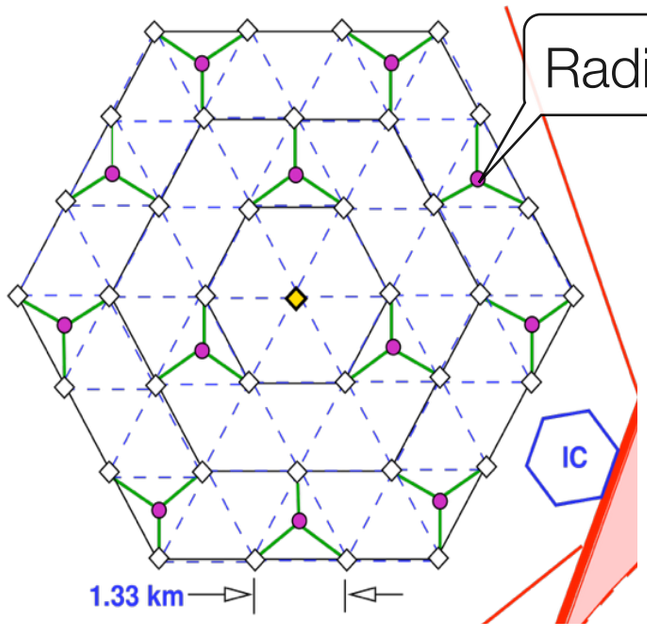
Increase of core density

PINGU

- **20-40 new strings** inside the DeepCore volume.
- **Energy threshold** reduced to **1 GeV.**
- Focus on measurement of **neutrino mass hierarchy.**

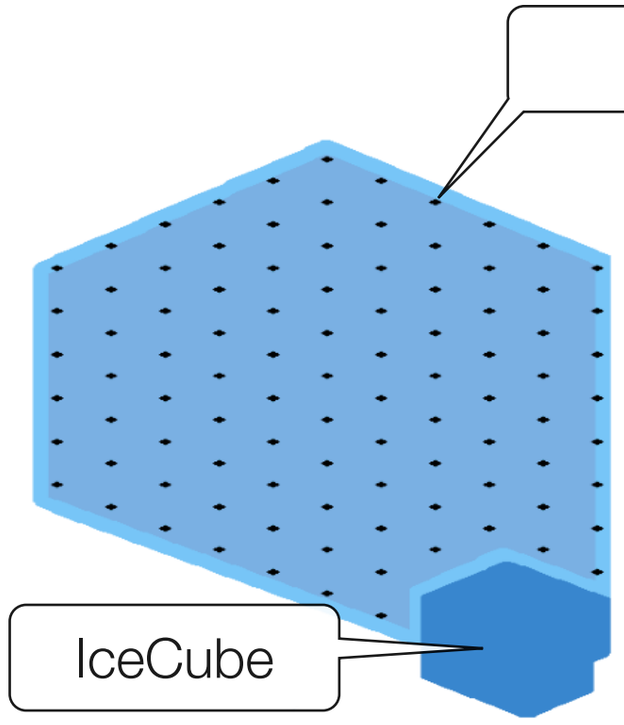


Extensions to larger volumes



Askarian Radio Array (ARA)

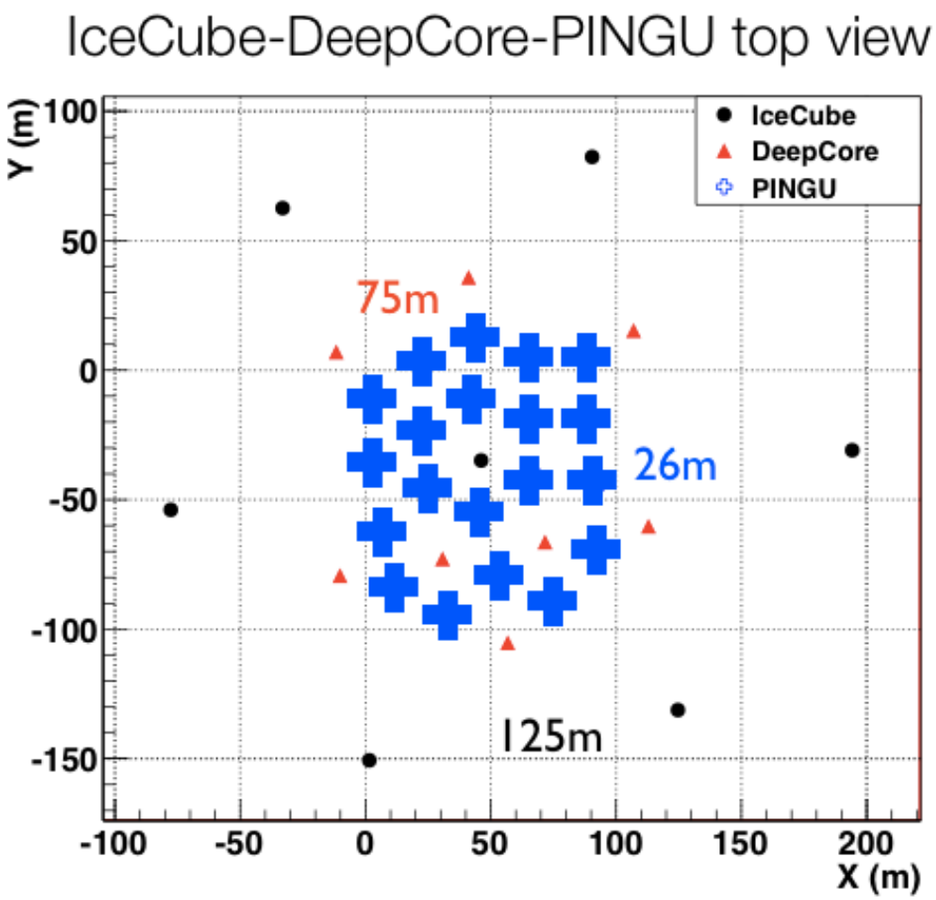
- InIce Radio array for **>30 PeV** neutrinos
- several **tens of km²** surface area

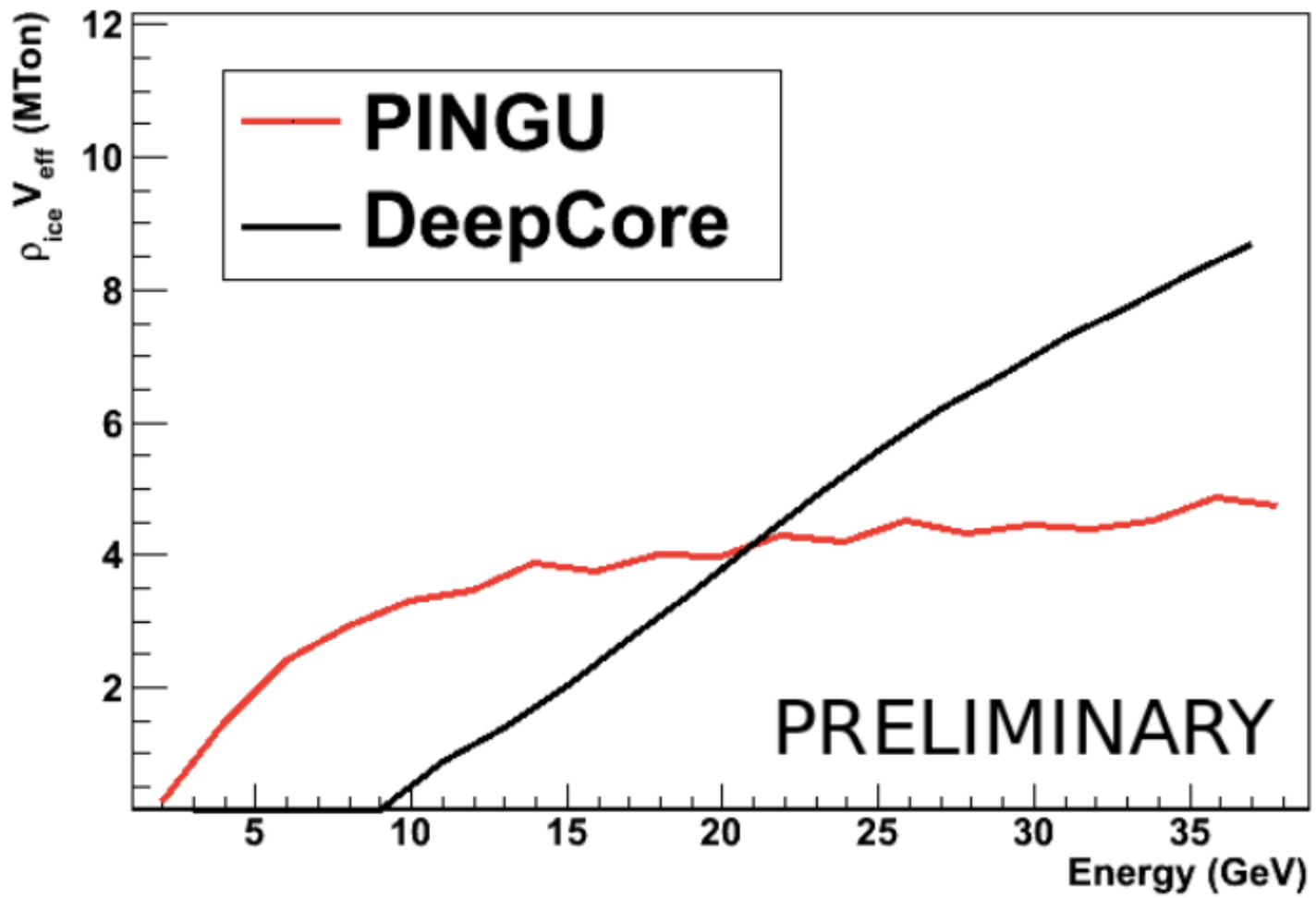


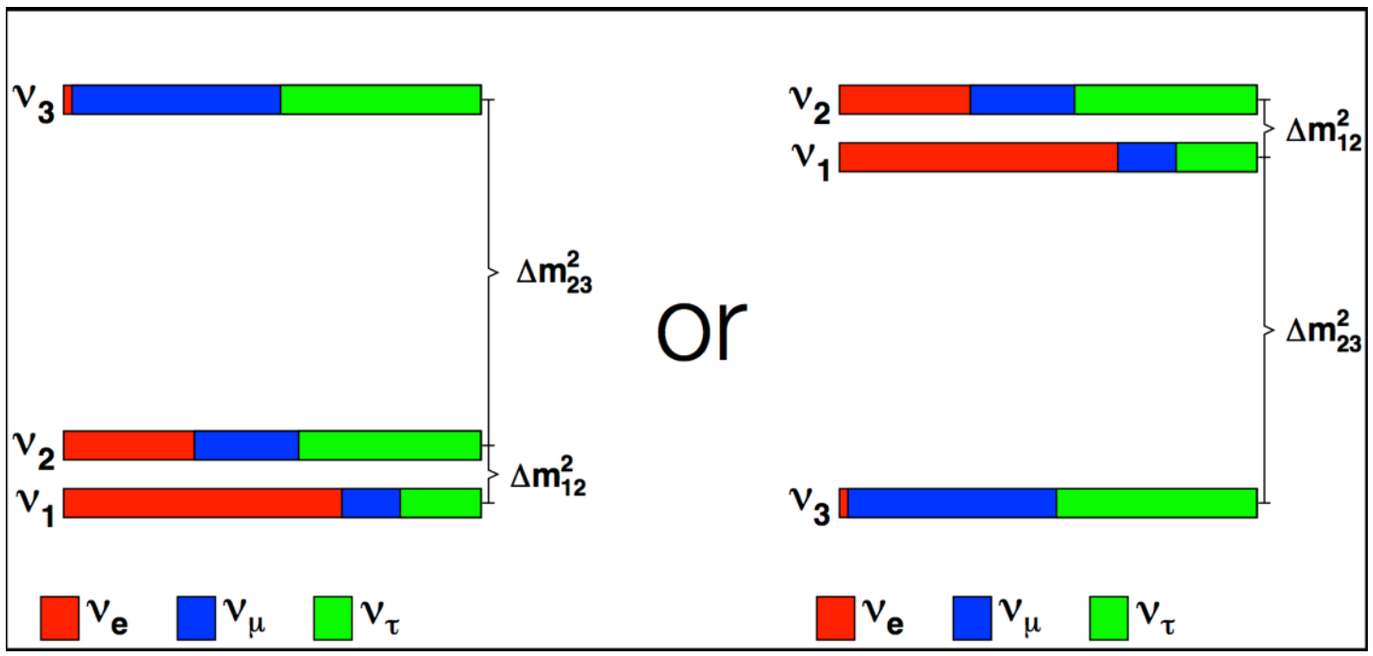
IceCube ++

- IceCube extension with **larger string spacing**
- Large **increase in effective area** above 10 TeV

Measurement of neutrino mass hierarchy with PINGU.



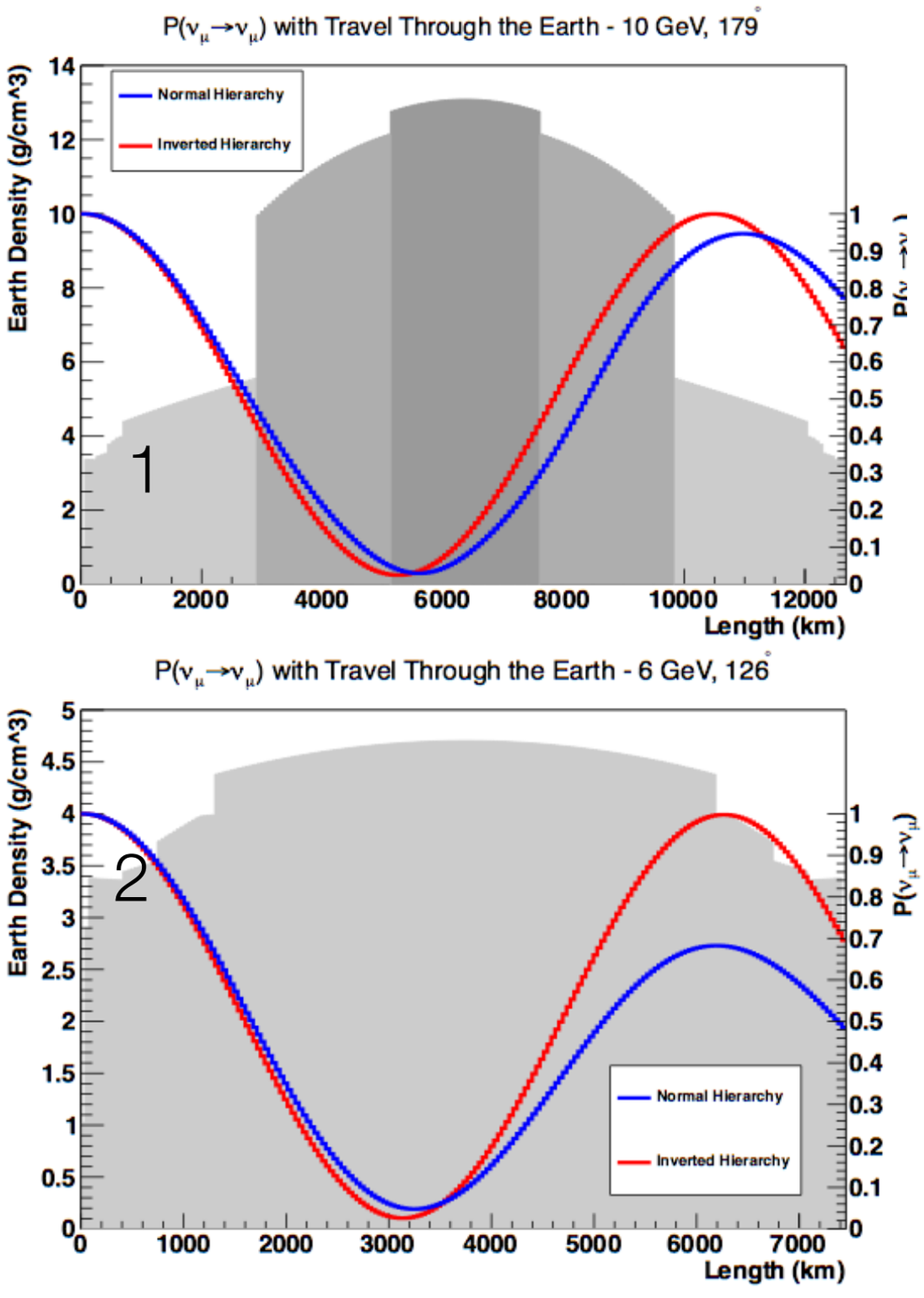


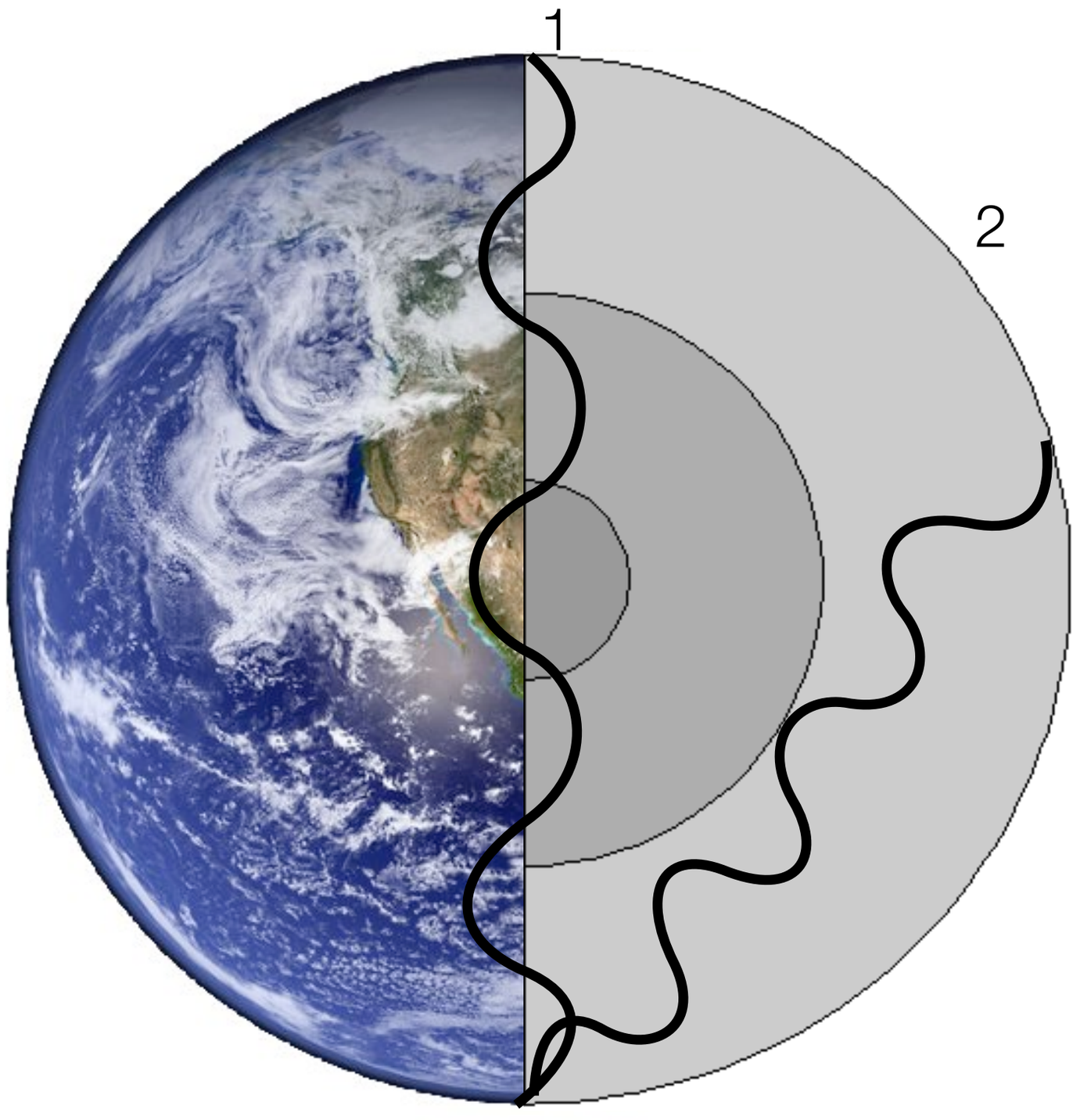


- **Mass hierarchy** is one of the last unknown fundamental properties of the neutrino sector.
- PINGU attempts to determine the hierarchy by providing a **megaton detector** for atm-ν with **1GeV threshold**.

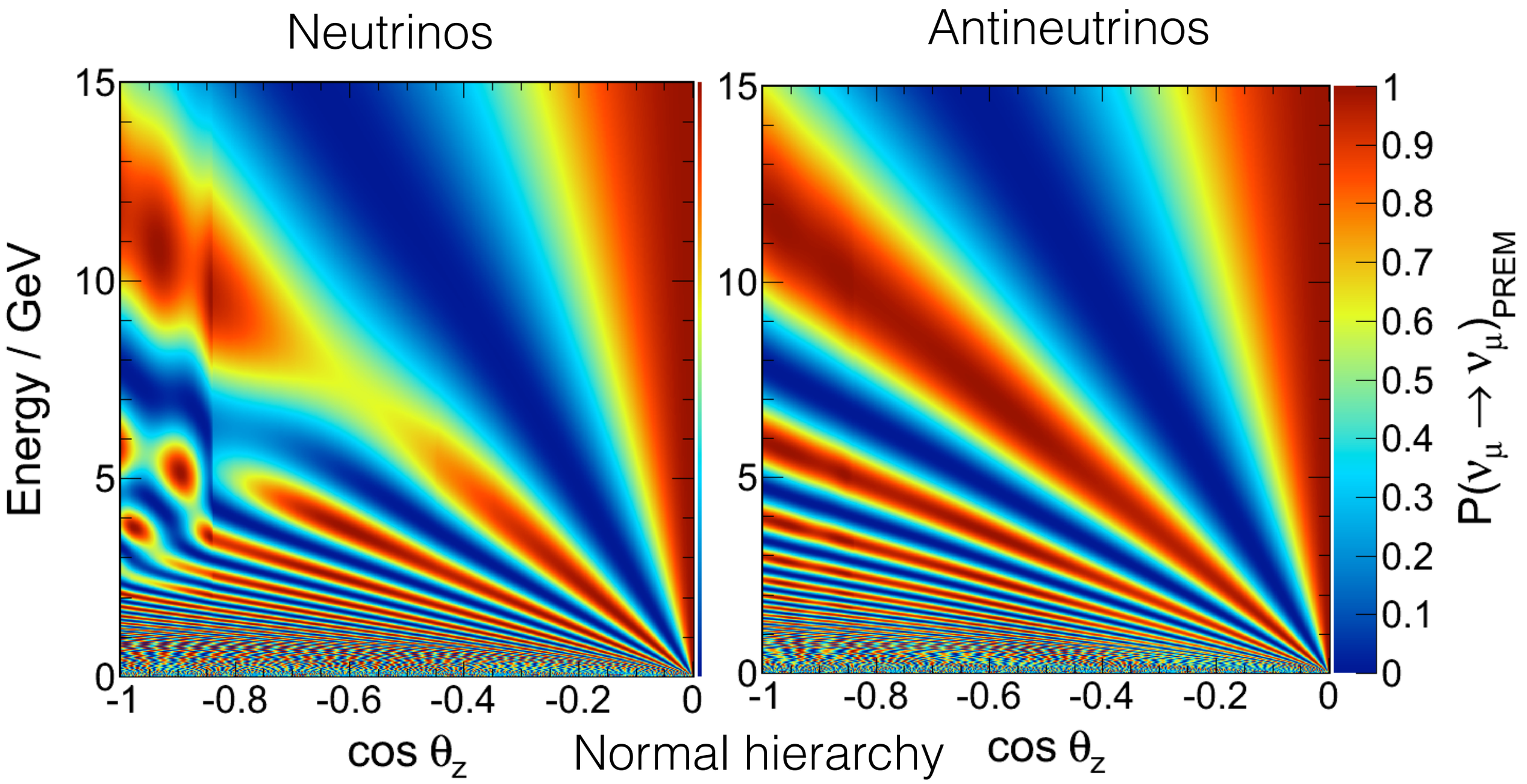
Measurement of neutrino mass hierarchy with PINGU.

- **Up to 20% differences** in ν_μ survival probabilities for various energies and baselines, depending on the neutrino mass hierarchy



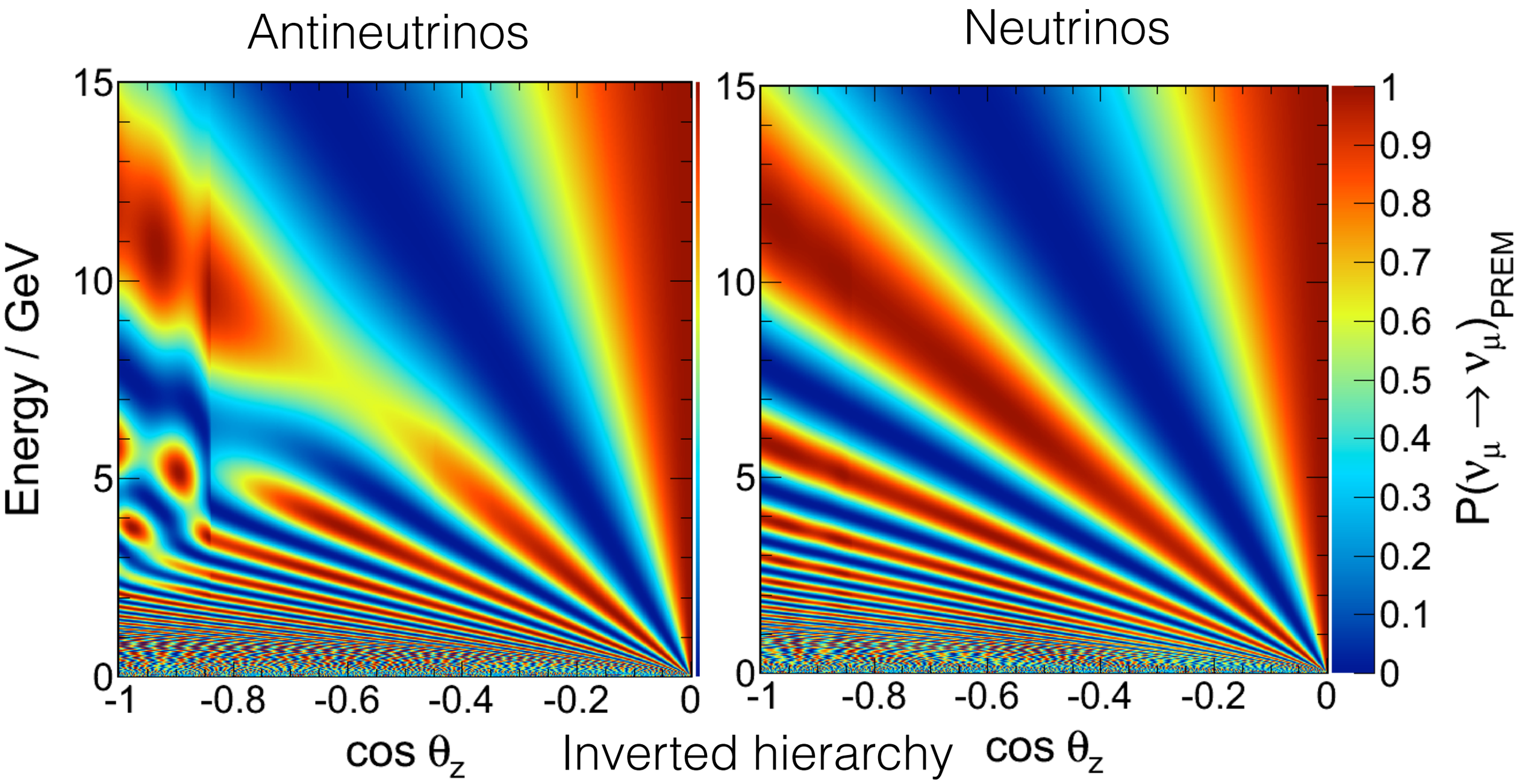


Muon neutrino survival probabilities for normal hierarchy.



> Survival properties for neutrinos and anti-neutrinos.

Muon neutrino survival probabilities for inverted hierarchy.



- **Survival probabilities switched** for neutrinos/anti-neutrinos in inverted hierarchy
- **PINGU cannot distinguish** neutrinos from anti-neutrinos ....
- ...but **rates** are **not the same**.

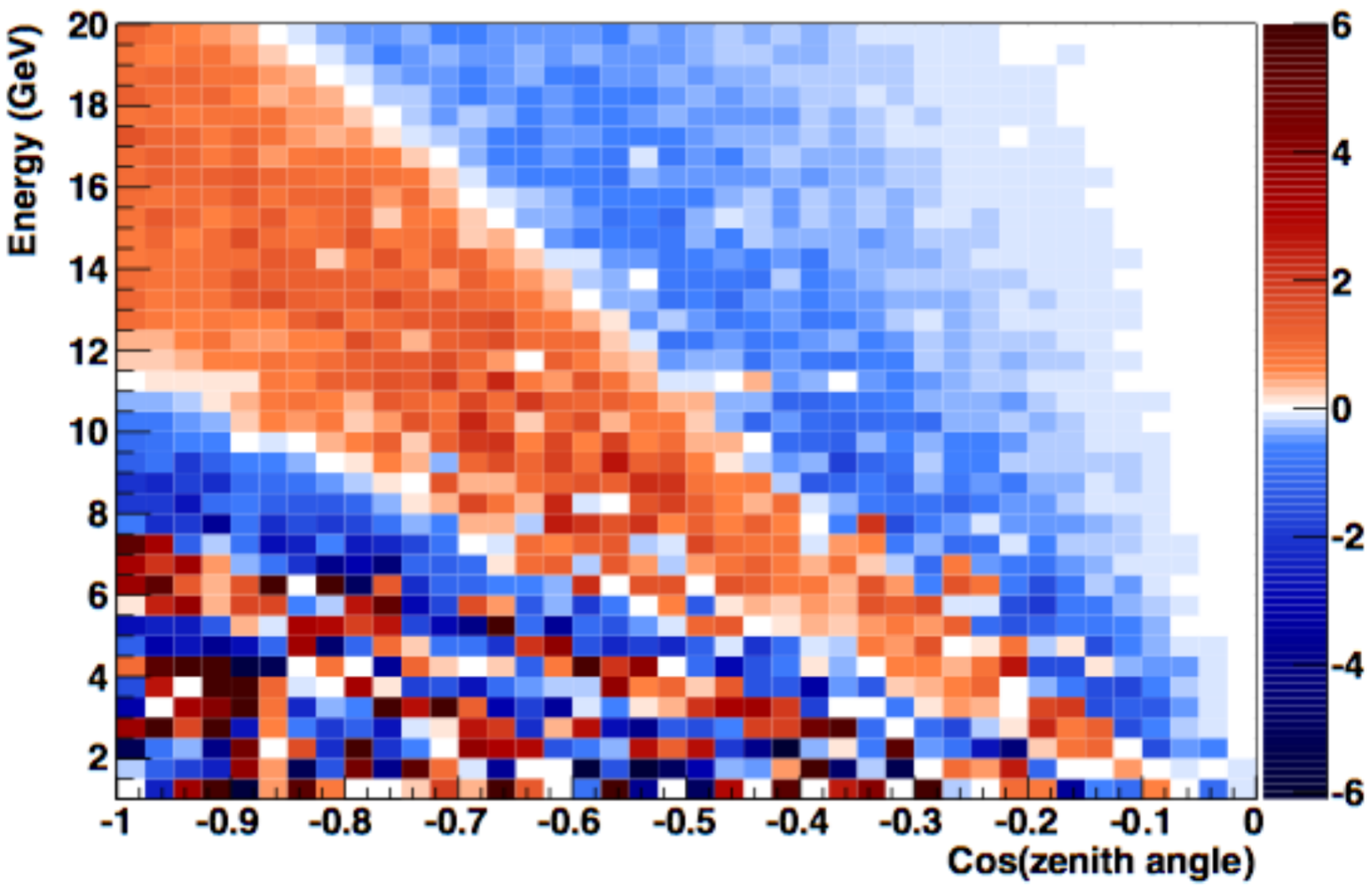
Measurement of mass hierarchy with PINGU.

> Need to measure **complicated pattern** in 2-dim distribution (E, cos(zenith))

> Good way to **visualize signature** of mass hierarchy:

- **Distinguishability metric** (Akhmedov, Razzaque & Smirnov (arXiv:1205.7071)):

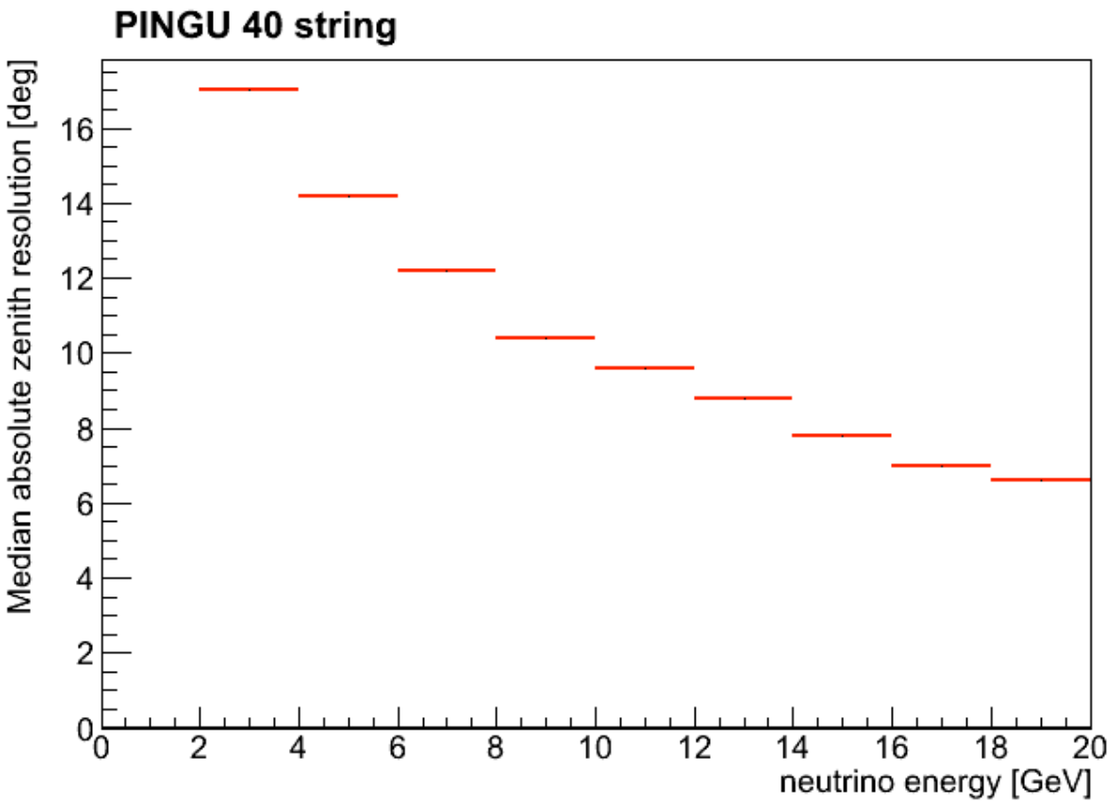
$$\frac{N_{obs,IH} - N_{obs,NH}}{\sqrt{N_{obs,NH}}}$$

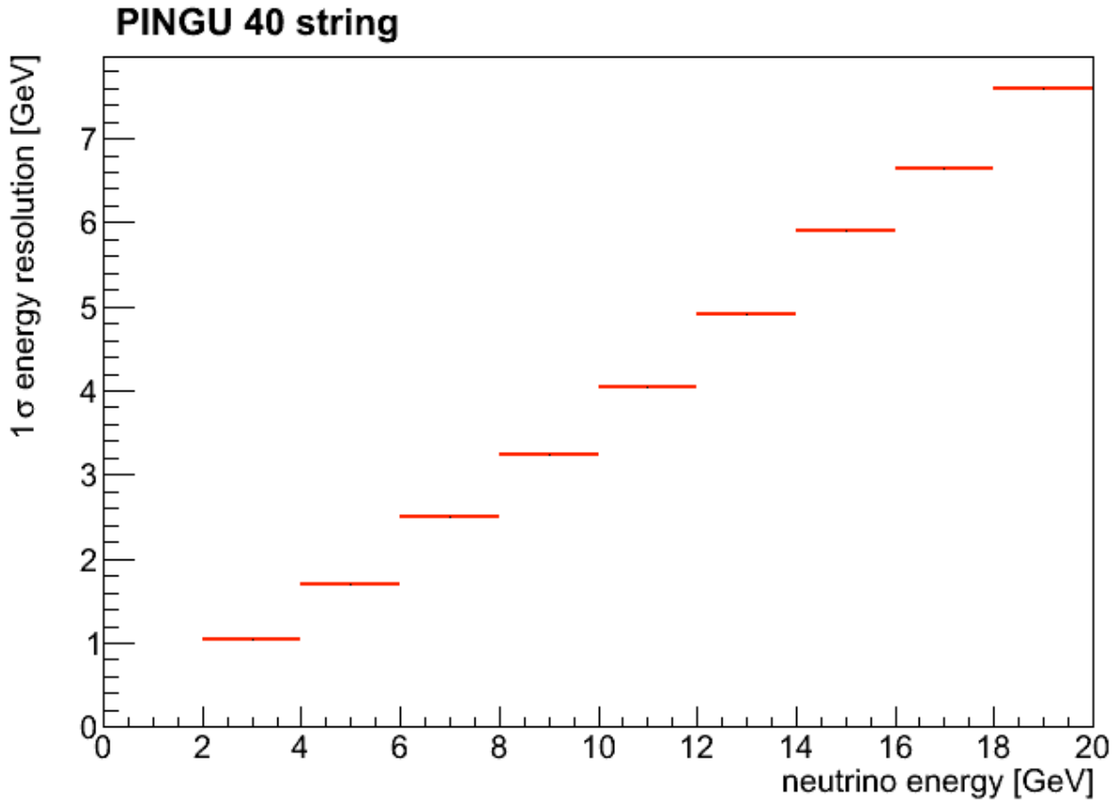


> Expected signal from inverted hierarchy in a **perfect detector.**

> Real detector will have **finite energy and zenith resolution**.

Performance studies for PINGU.



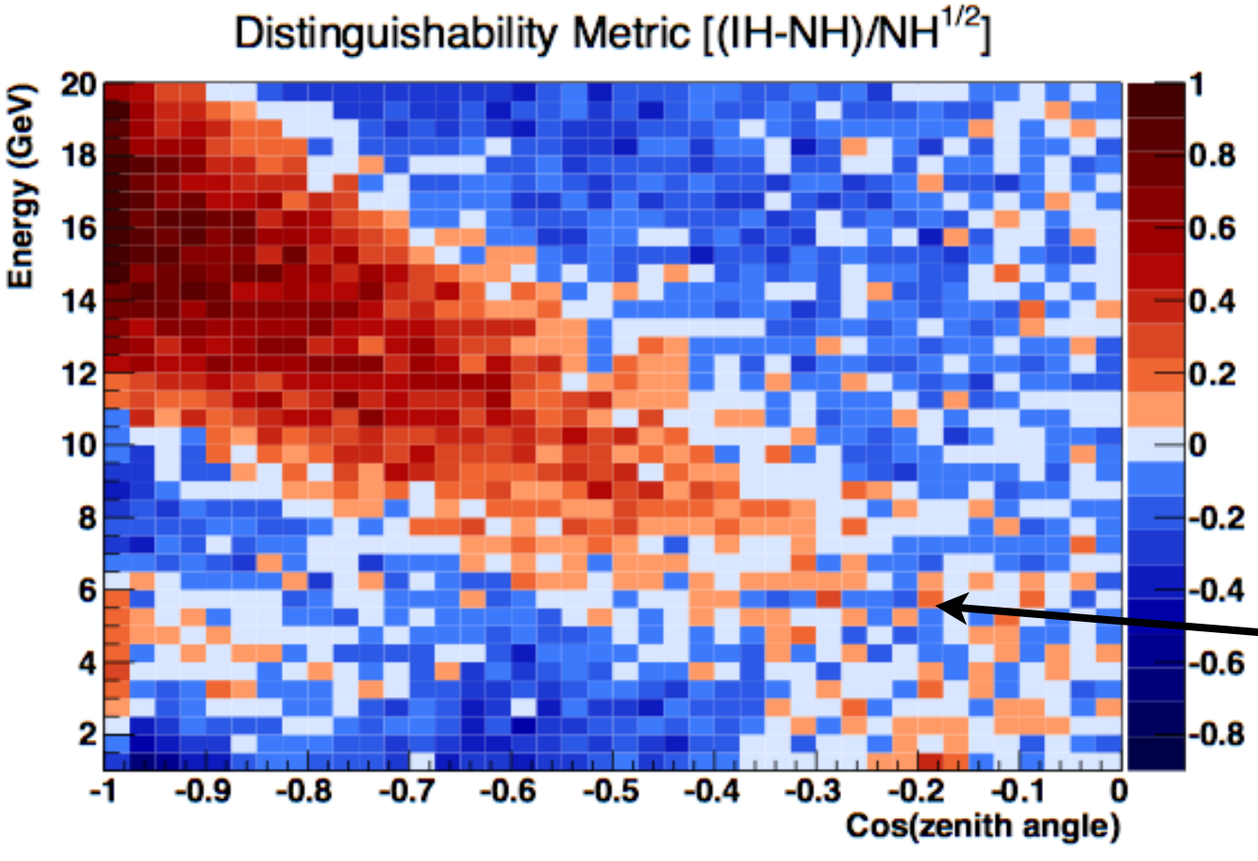


- Currently using **DeepCore algorithms** for reconstruction.

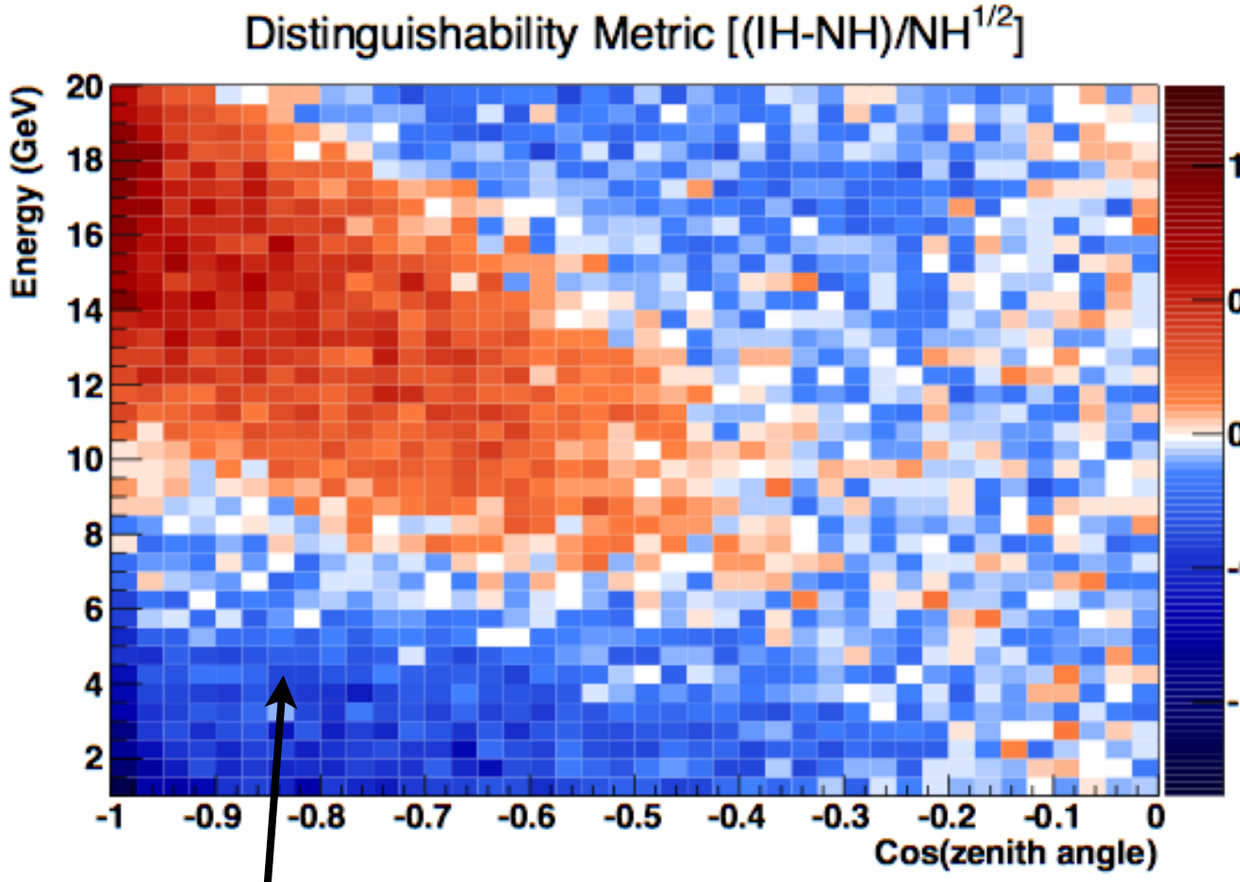
- **Systematics** studied so far:
  - θ_{23}, θ_{13}, Δm^2_{atm}, δ_{CP} within world average ±2σ ranges
  - Efficiency errors (30%)
  - Atmos. ν spectral index (±0.05)
  - Energy calibration (10% bias)
  - Pointing accuracy (10% bias)
  - Energy resolution (10% error)
  - Angular resolution (10% error)
  - Further studies underway now.

Measurement of mass hierarchy with PINGU.

> Good **identification of mass hierarchy** possible with realistic experimental resolution.



Zenith resolution: 10°
Energy resolution 1 GeV

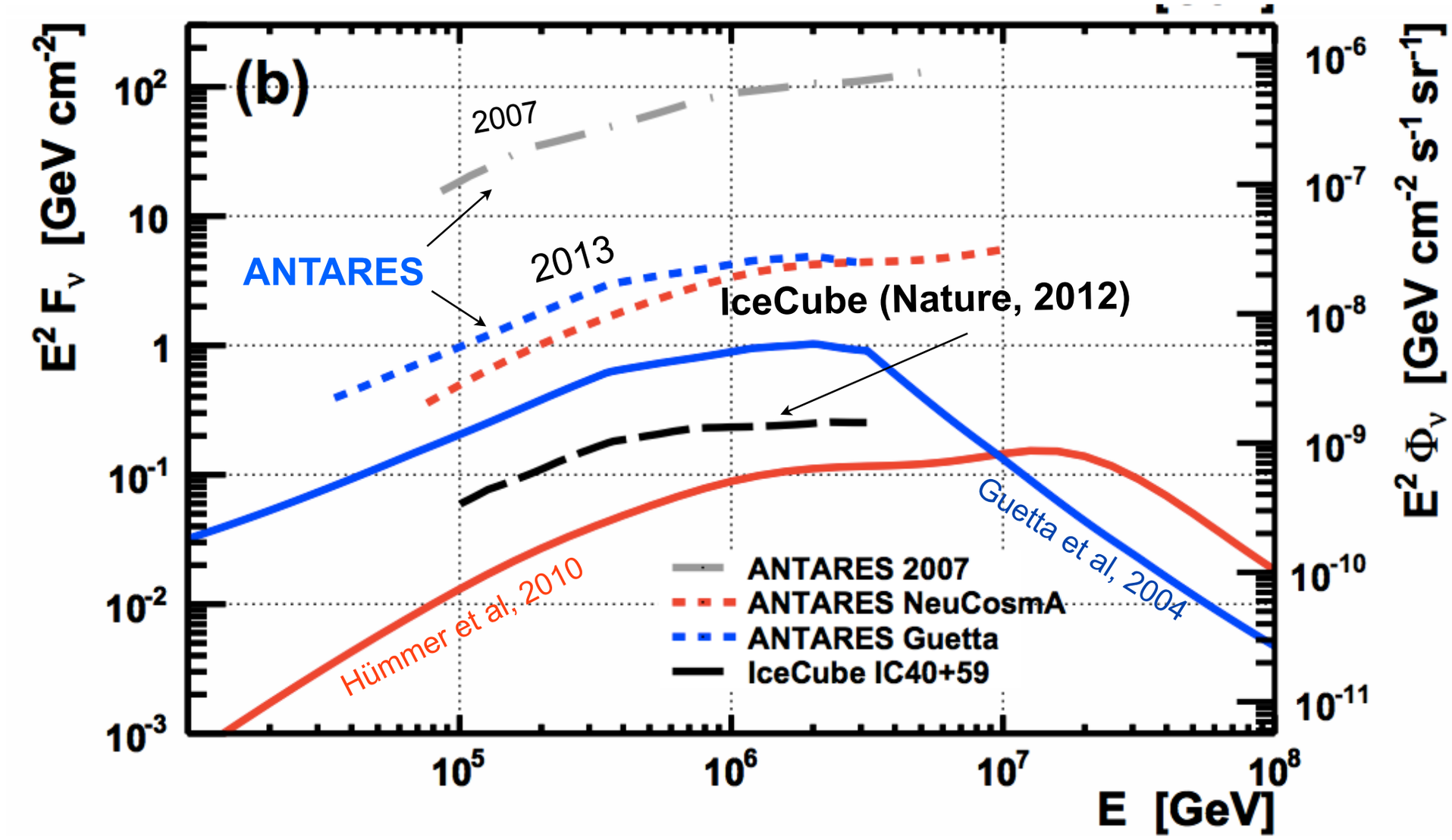


Zenith resolution: 12.5°
Energy resolution 3 GeV

conservative scenario

optimistic scenario

Search for neutrinos from GRBs.



IceCube

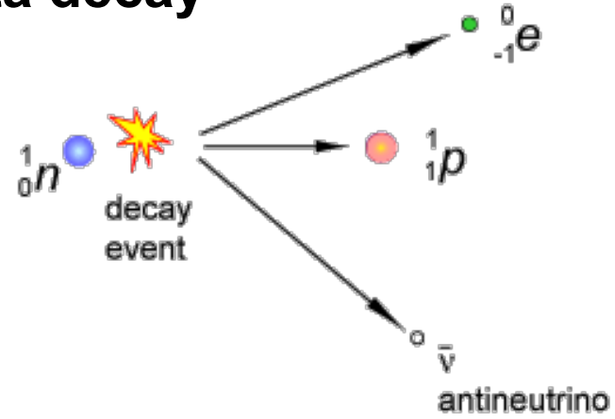
- **225 GRB** at Northern sky
- 2 years of IceCube construction phase data
- No significant correlation found between IceCube events and GRBs.

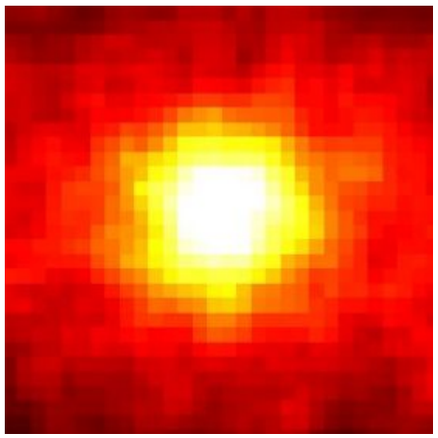
ANTARES

- **296 GRB at** Southern sky
- No ANTARES event in time and direction coincidence (arXiv:1307.0304)

Production mechanisms of neutrinos (in space).

Beta decay

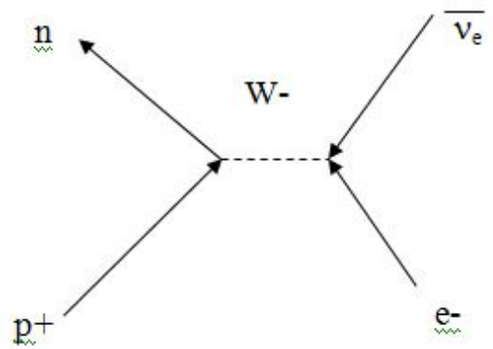


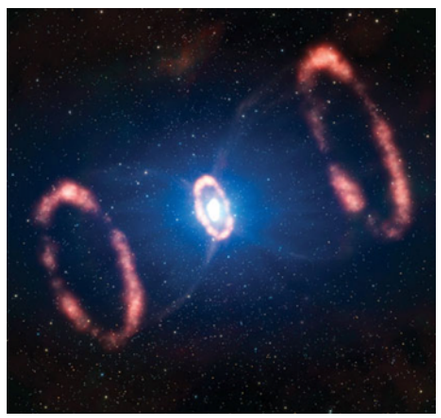


Neutrino image of the sun

> Neutrinos from the sun.
  - MeV energies

Electron capture

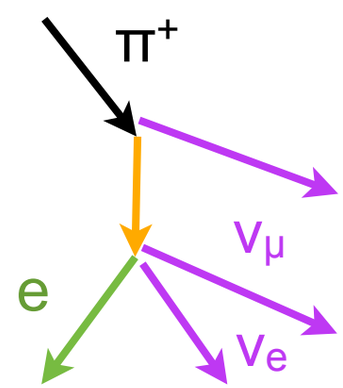


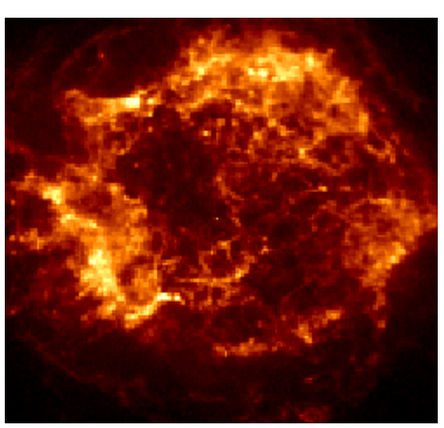


SN 1987A

> Core-collapse supernovae.
  - MeV energies

Decays of mesons





Cas A

> Particle acceleration sites in the universe.
  - up to 10^{12} MeV

Potential of neutrinos for astronomy…

> …was already seen in 1960 by G. Marx

Cosmic Neutrino Radiation

Abstract. New and more powerful methods for eliminating background intensity are needed in order to make possible the development of neutrino astronomy into a new, far-reaching branch of science.

The result of the small capture cross section of the neutrino is that the mean free path of the neutrinos of the 1 to 10 Mev energy region in the universe amounts to about 10^{80} light-years (that of the antineutrino is a little less). From this it follows that neutrino radiation offers a very useful opportunity for observation of events very distant in space and time (in principle, up to 10^{80} light-years and 10^{80} years, respectively), provided, naturally, that the problem of detection can be solved. For example,

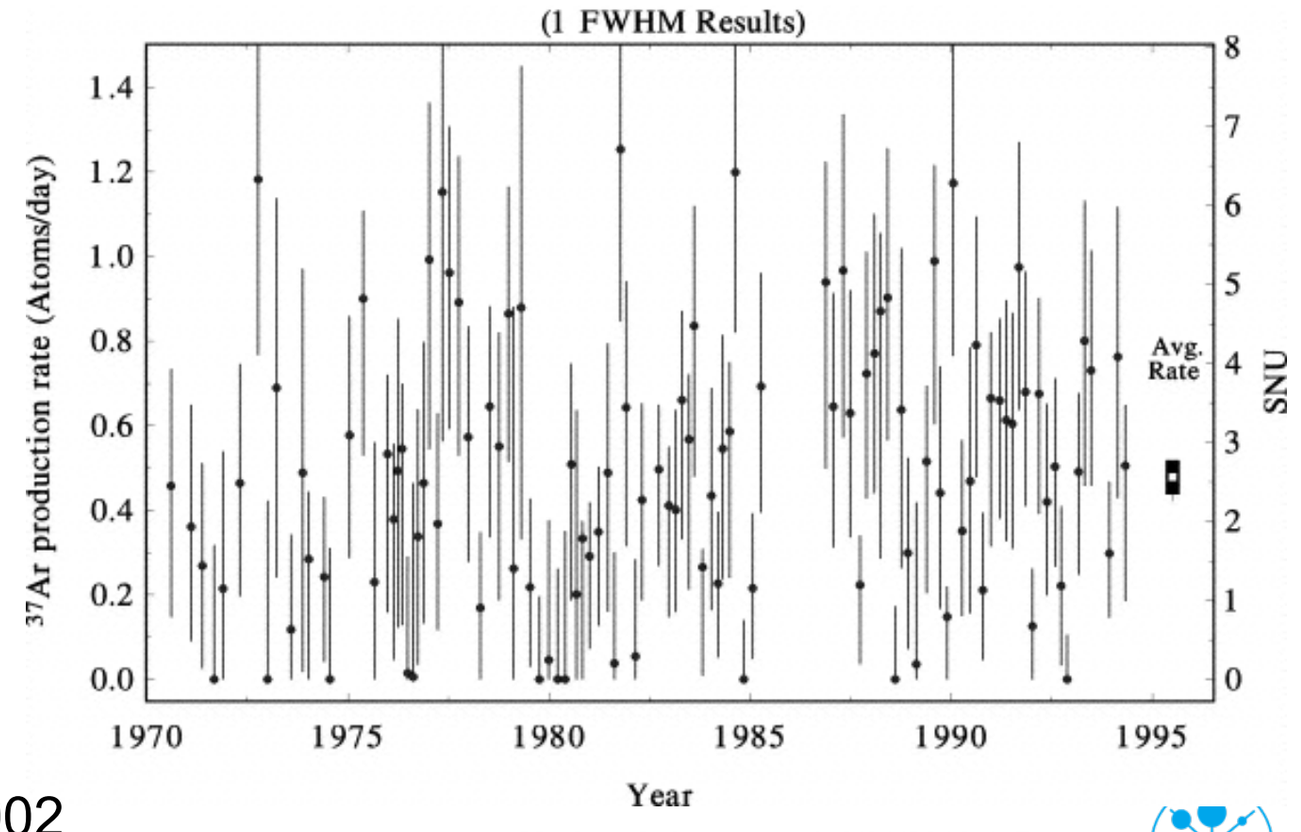
Science, 131 (1960)

The dawn of neutrino astronomy: The Homestake experiment.

- 615 tons of tetrachloroethylene, ~1500 m underground.
- Observations of solar neutrinos by

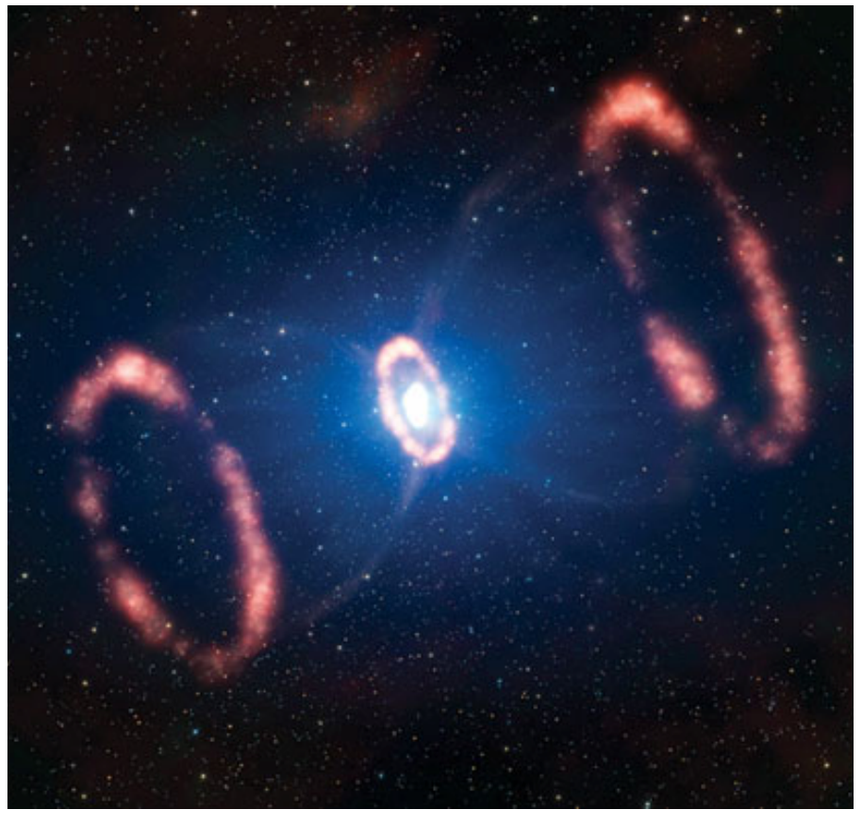
$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^- \ .$$

- Discrepancy found from expectations for neutrino production in the sun.
  - eventually resolved by discovery of neutrino oscillations



Raymond Davis, Nobel Prize 2002

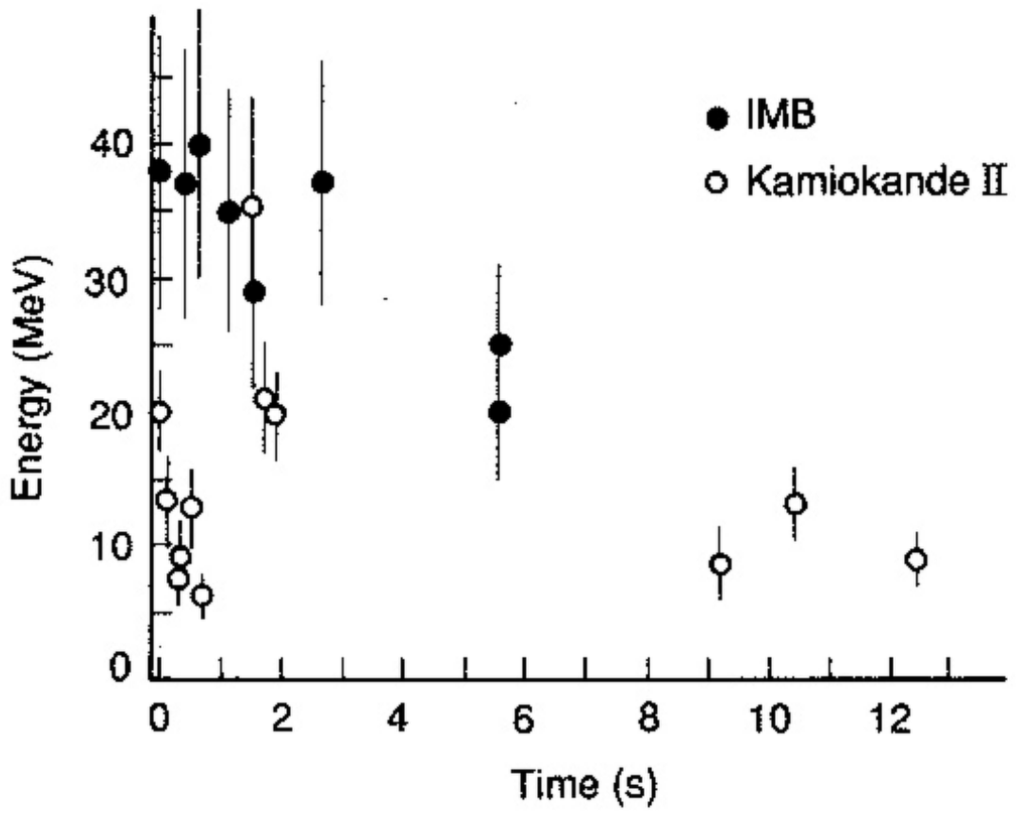
The first breakthrough: Neutrinos from SN 1987A



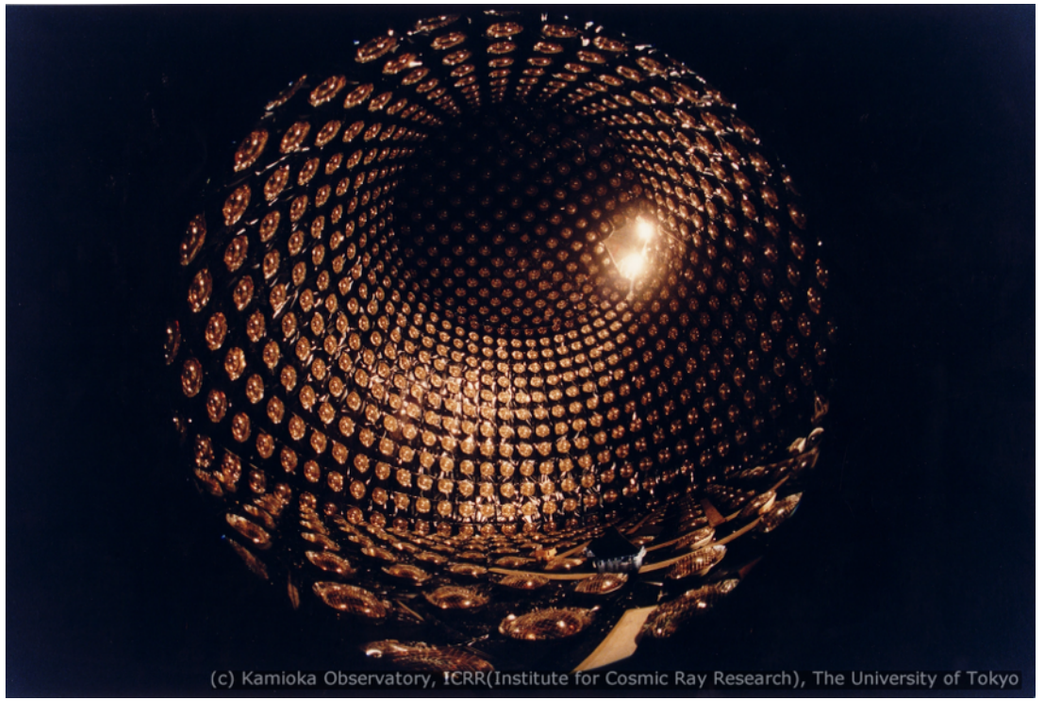
> **Supernova** in the Large Magellanic Cloud (~50 kpc from Earth).

> **Neutrino burst observed** by two underground detectors.

- Confirming the core-collapse model for supernovae

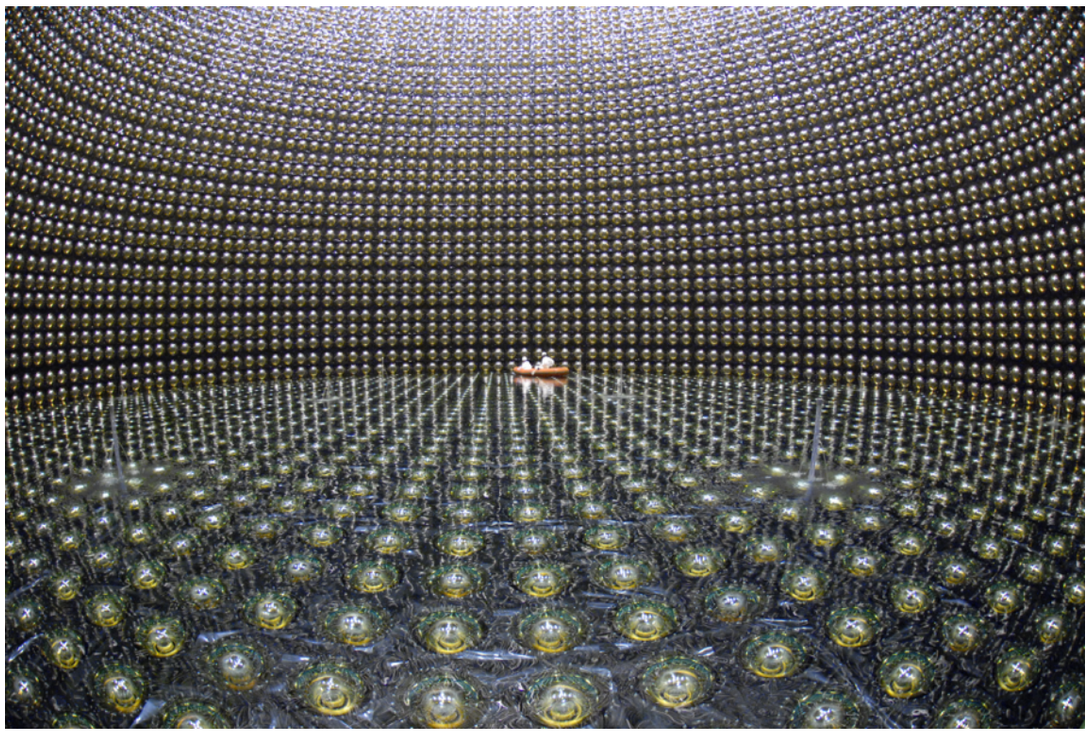


Kamiokande II detector.

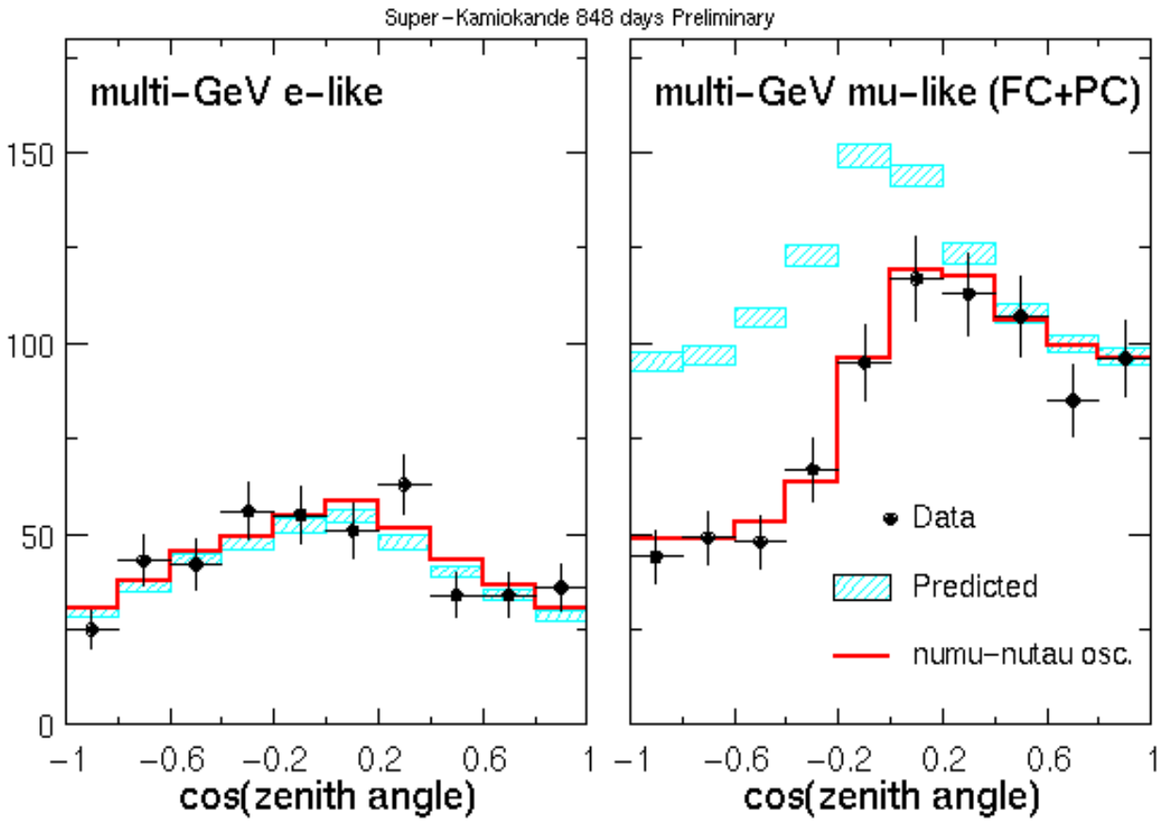


M. Koshiba, Nobel Prize 2002

The surprise: Neutrinos have mass.



Super-Kamiokande detector



> Neutrinos **have** (very low) **masses.**

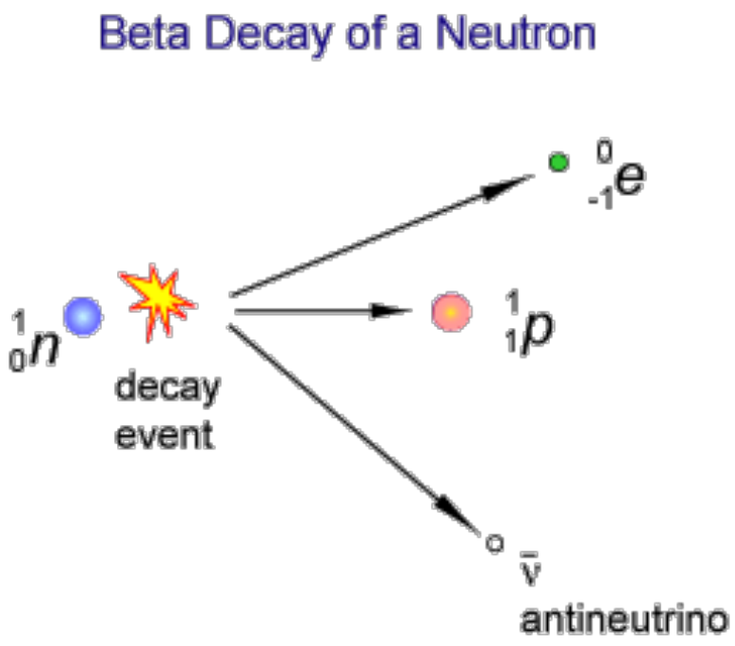
> Neutrinos **oscillate** between their **flavors** ν_e, ν_μ, ν_τ.

> **ν_e from the sun** seem to “disappear” on their way to Earth.

> **ν_μ in the atmosphere** seem to “disappear” from certain directions.

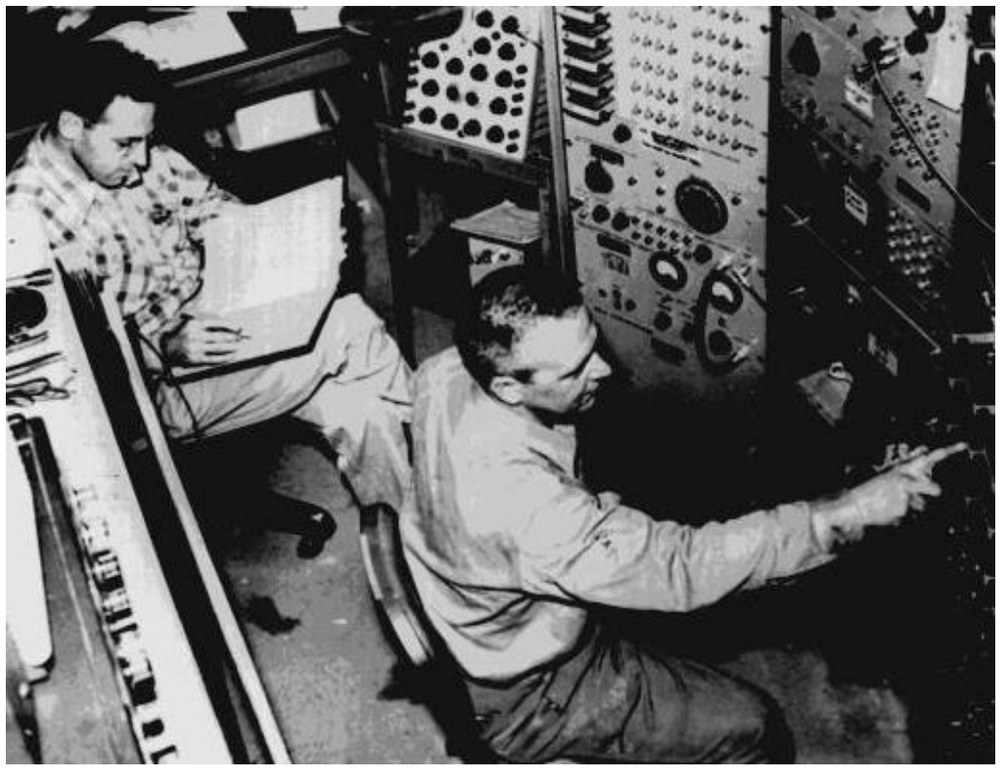
> Observed by underground detectors in Japan & Canada.

Neutrinos: A brief history.



> **Postulated** by W. Pauli to “rescue” the energy conservation principle in nuclear beta decays.

> Possibility to detect neutrinos in inverse beta decays, but **reactions are very rare**.

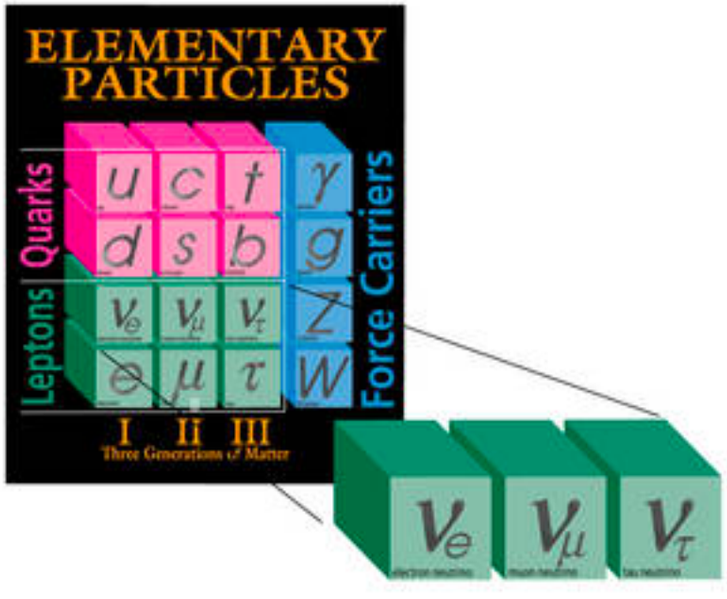


> It took the advent of **nuclear reactors** to discover neutrinos experimentally.

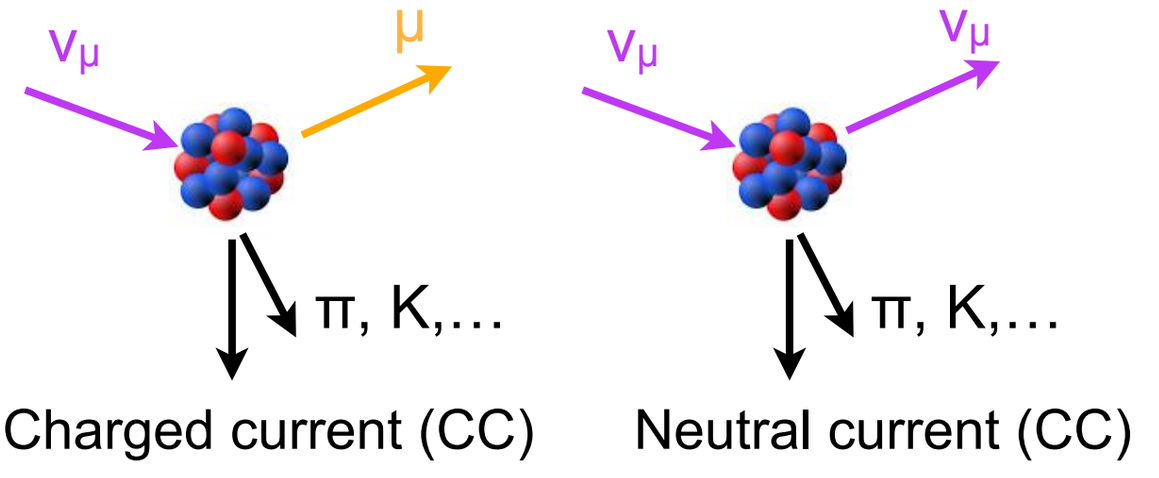
- Reactor provided 10^{13} neutrinos / cm^2 / s

> Experiment by C. Cowen & F. Reines (Nobel price 1995)

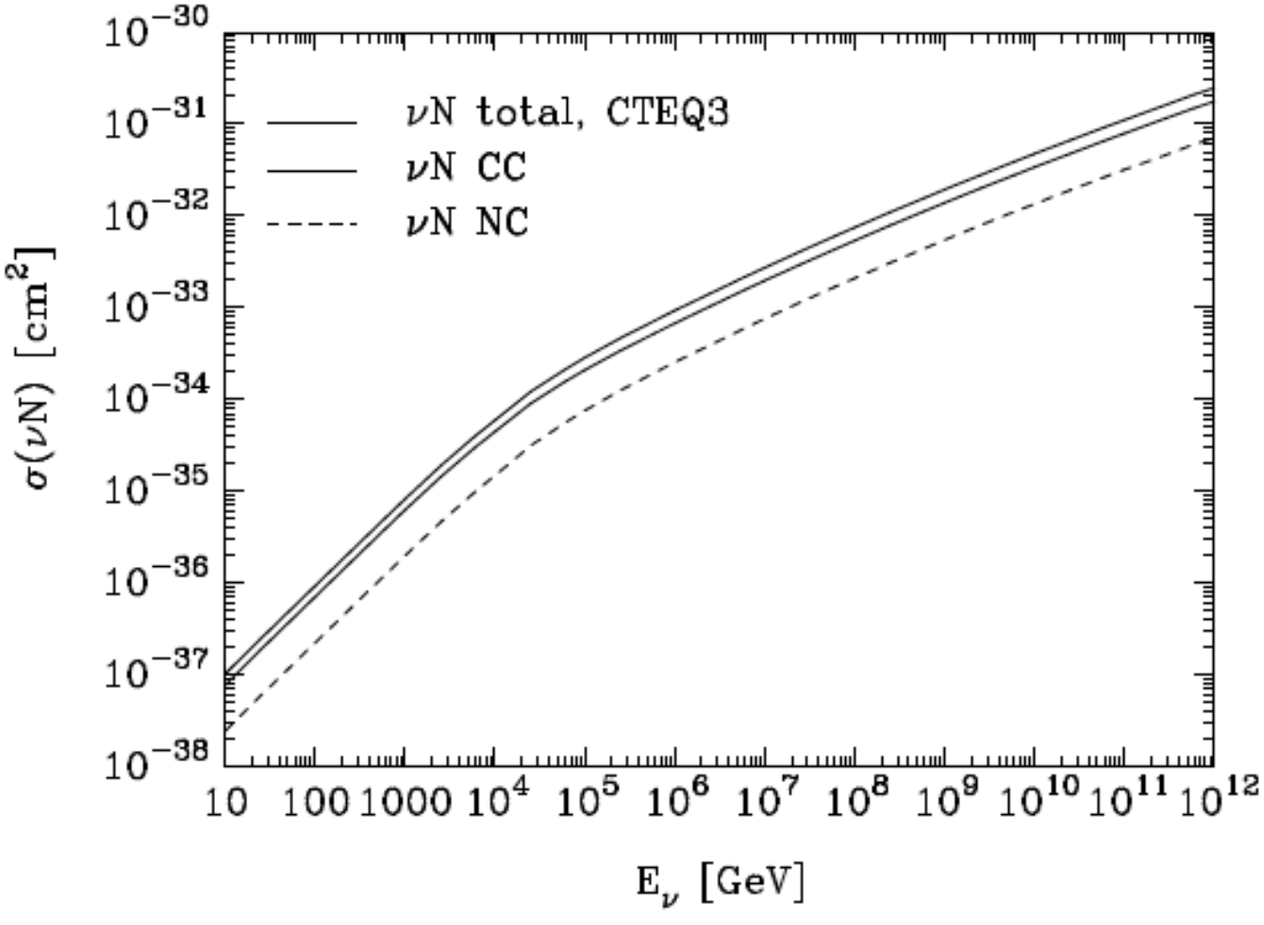
Some properties of neutrinos.



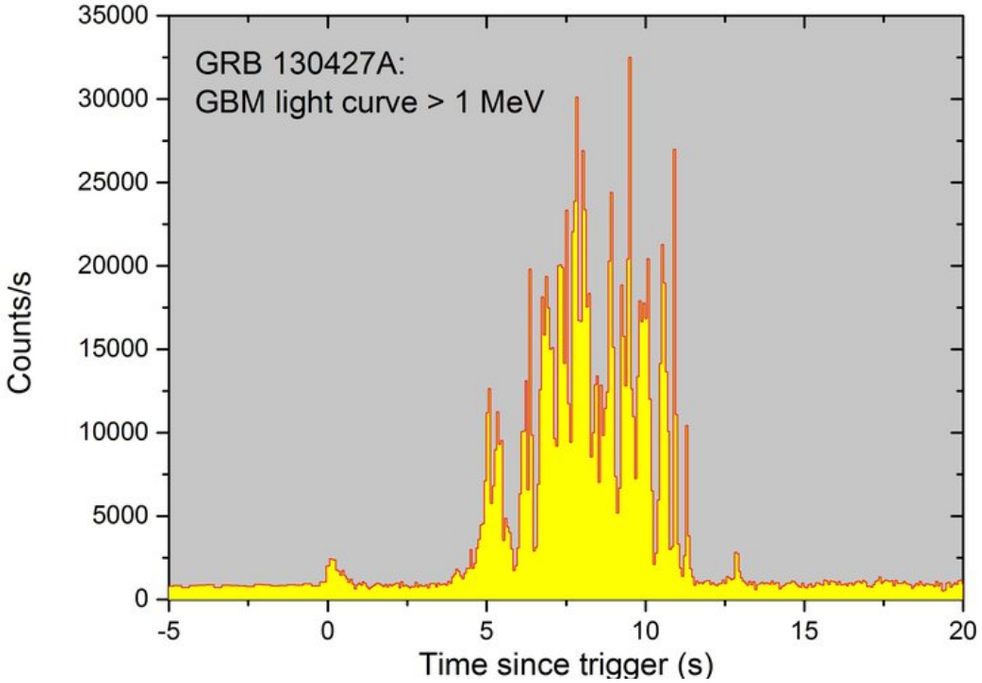
- Three flavors of neutrinos.
  - Neutral & almost massless.
- Low interaction cross-section
  - Enables them to penetrate dense matter.
  - Interaction length of neutrinos (@1 TeV) in water: **2.5 10^6 km (!)**

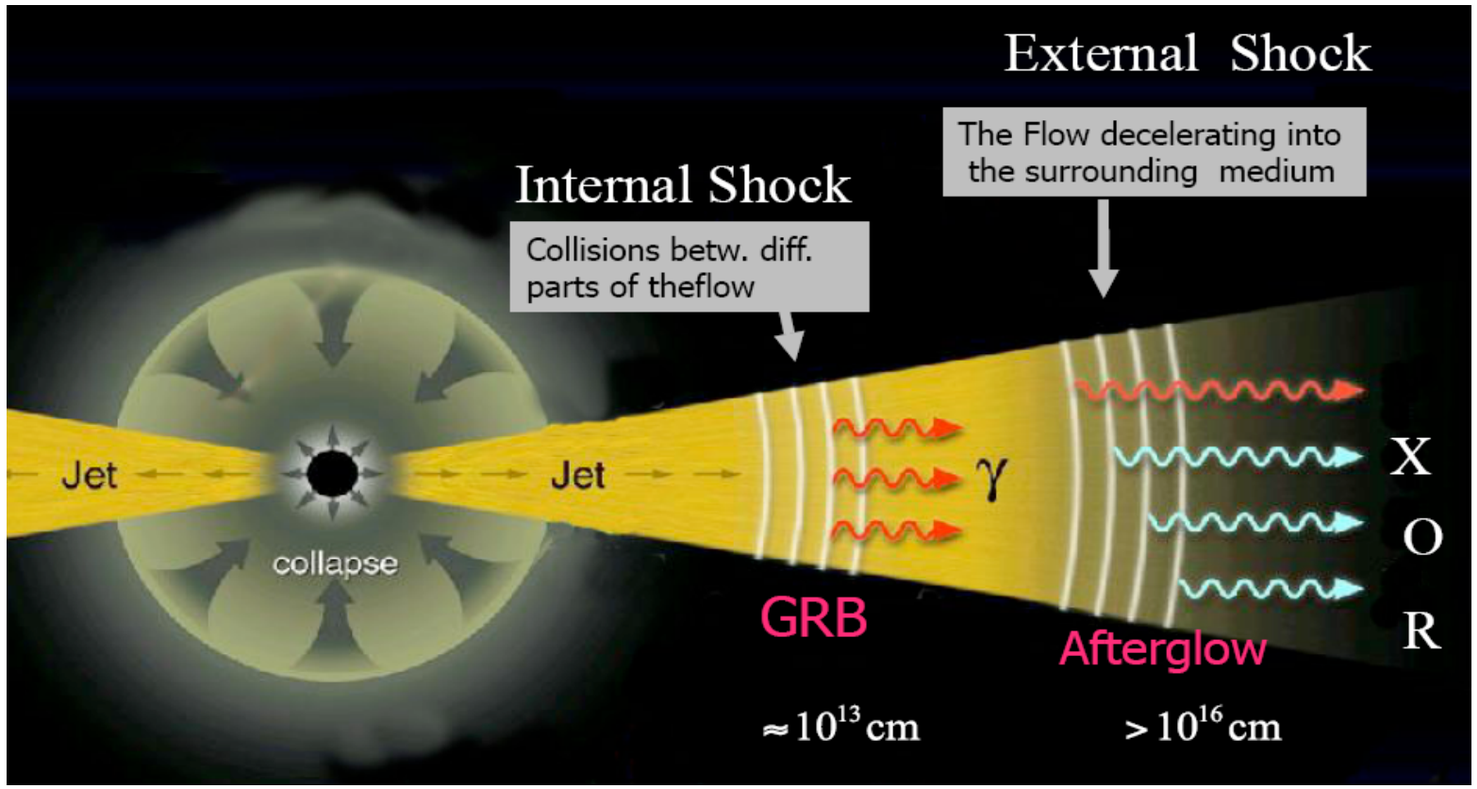


Inelastic scattering of neutrinos off nuclei



Search for neutrinos from transients: GRBs



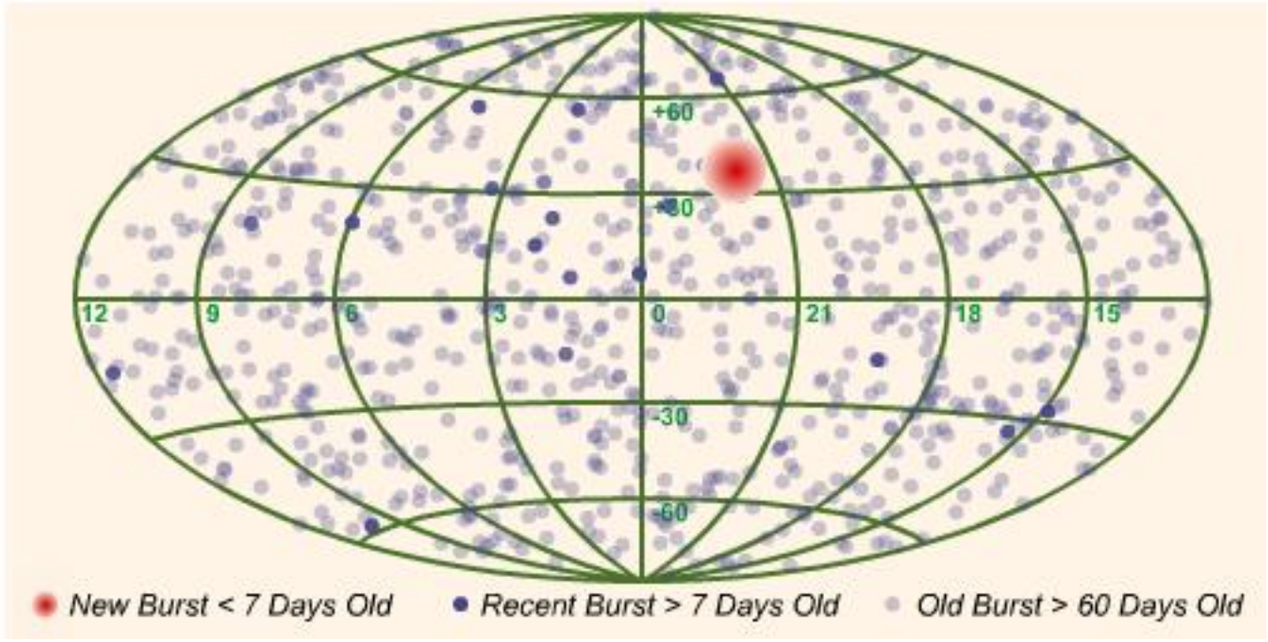


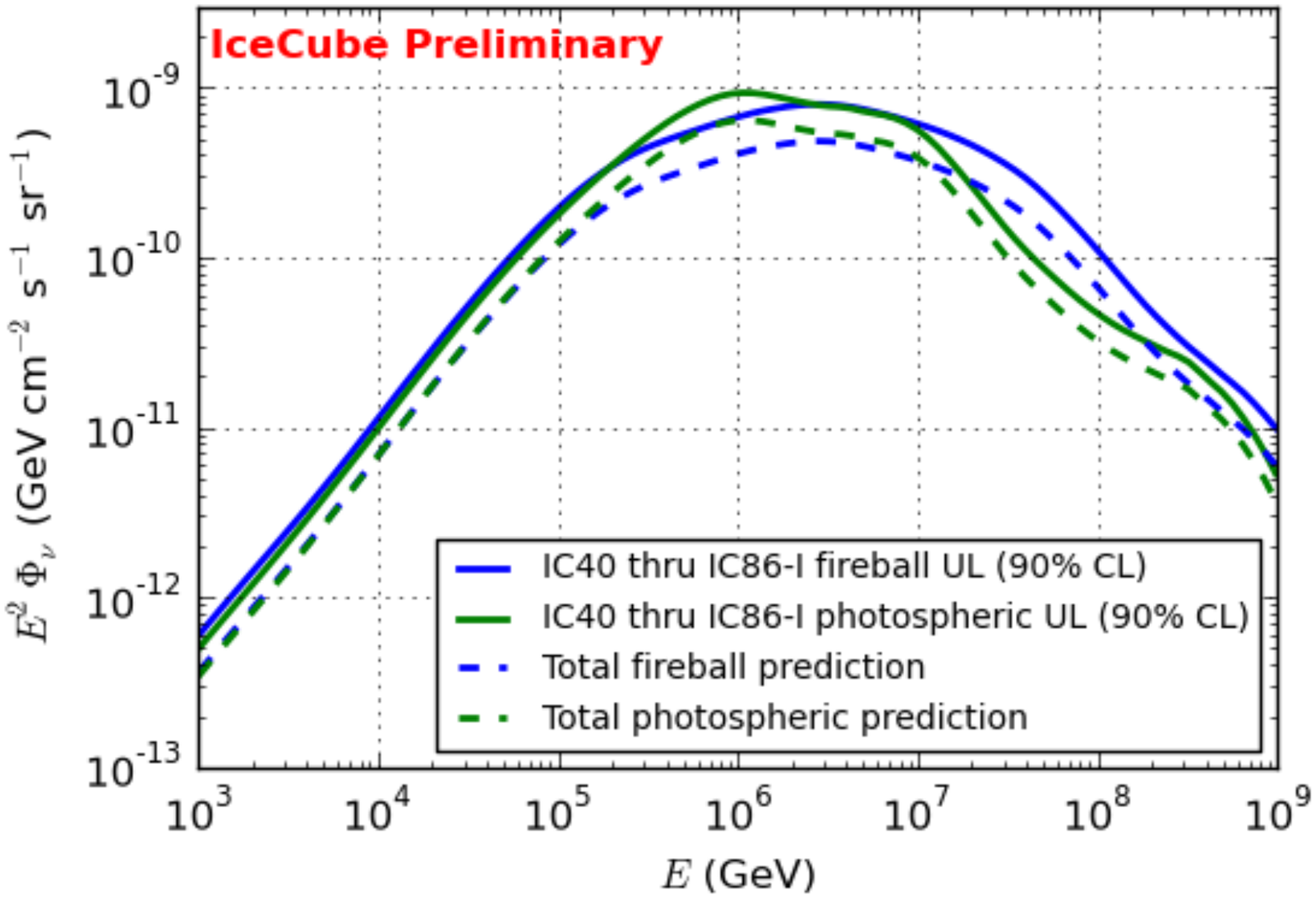
- **Gamma-ray bursts:** huge amounts of energy released in gamma rays over O(s)
  - Has been connected to core collapse SNe of massive stars and mergers of compact objects

- GRB have been proposed as the **dominant acceleration site** for CRs up to energies > 10^{20} eV.
- Accompanying **neutrino emission** should be **visible in km^3-sized** neutrino telescopes in a wide variety of scenarios.

Search for neutrinos from GRBs.

- **Search for** cumulative signal from all available bursts.
- Observations are **compatible with expectations** from the atmospheric background.

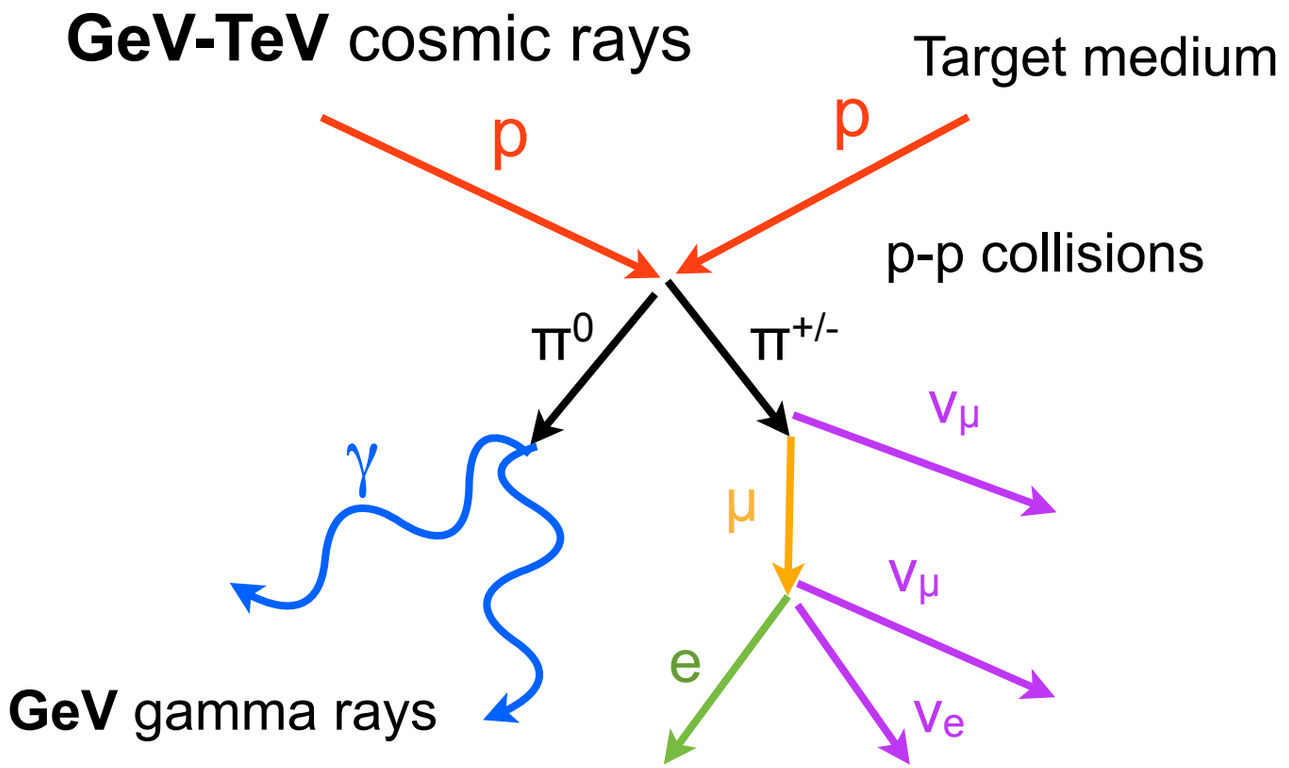




- **Upper limits** from the analysis of 568 GRBs (4 years of IceCube data)
- Limits close **to predictions of GRB signal** (if GRBs dominate CR production)**.**

The cosmic-ray / gamma / neutrino connection (II)

- Cosmic rays interact with a target medium close to the source.
- Neutrino/Gamma production via p-p collisions.
- GeV gamma-ray spectrum correlated to GeV neutrino spectrum.



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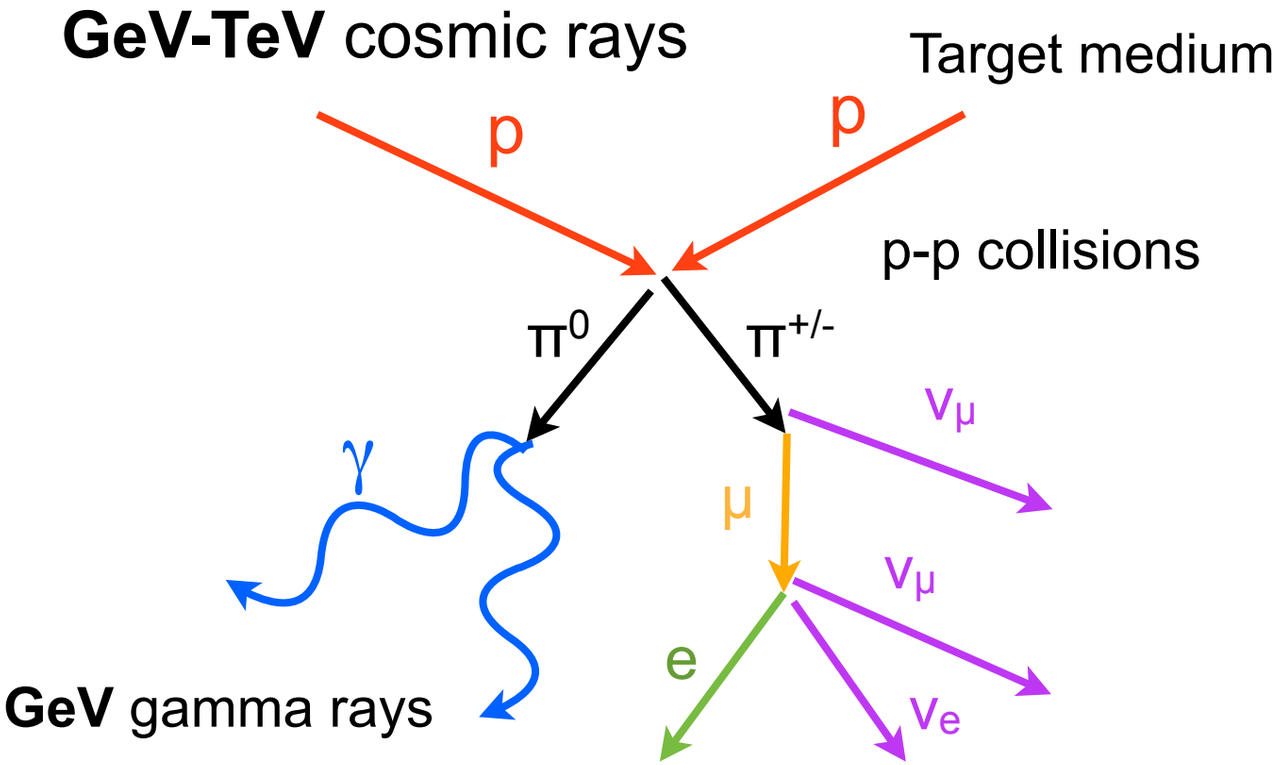
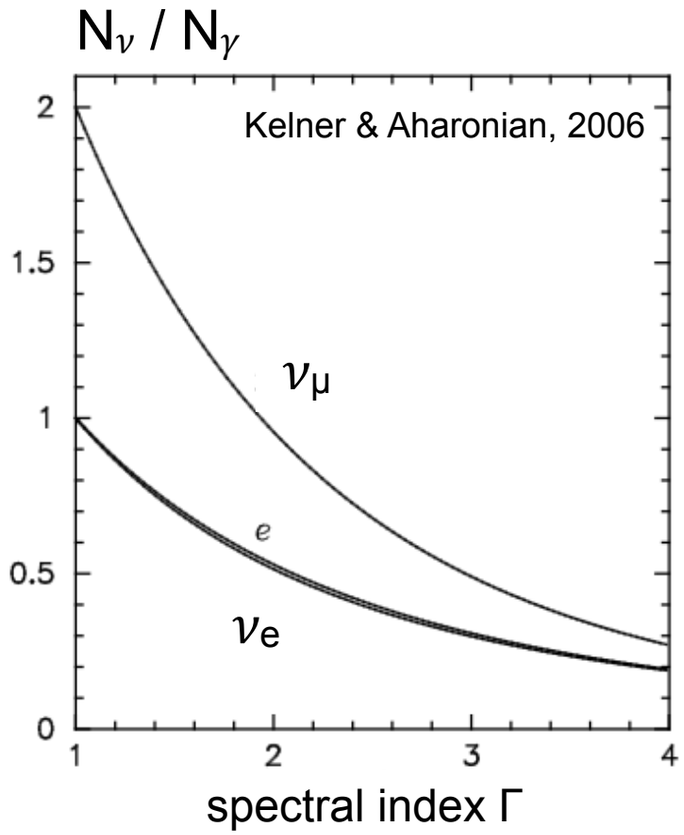
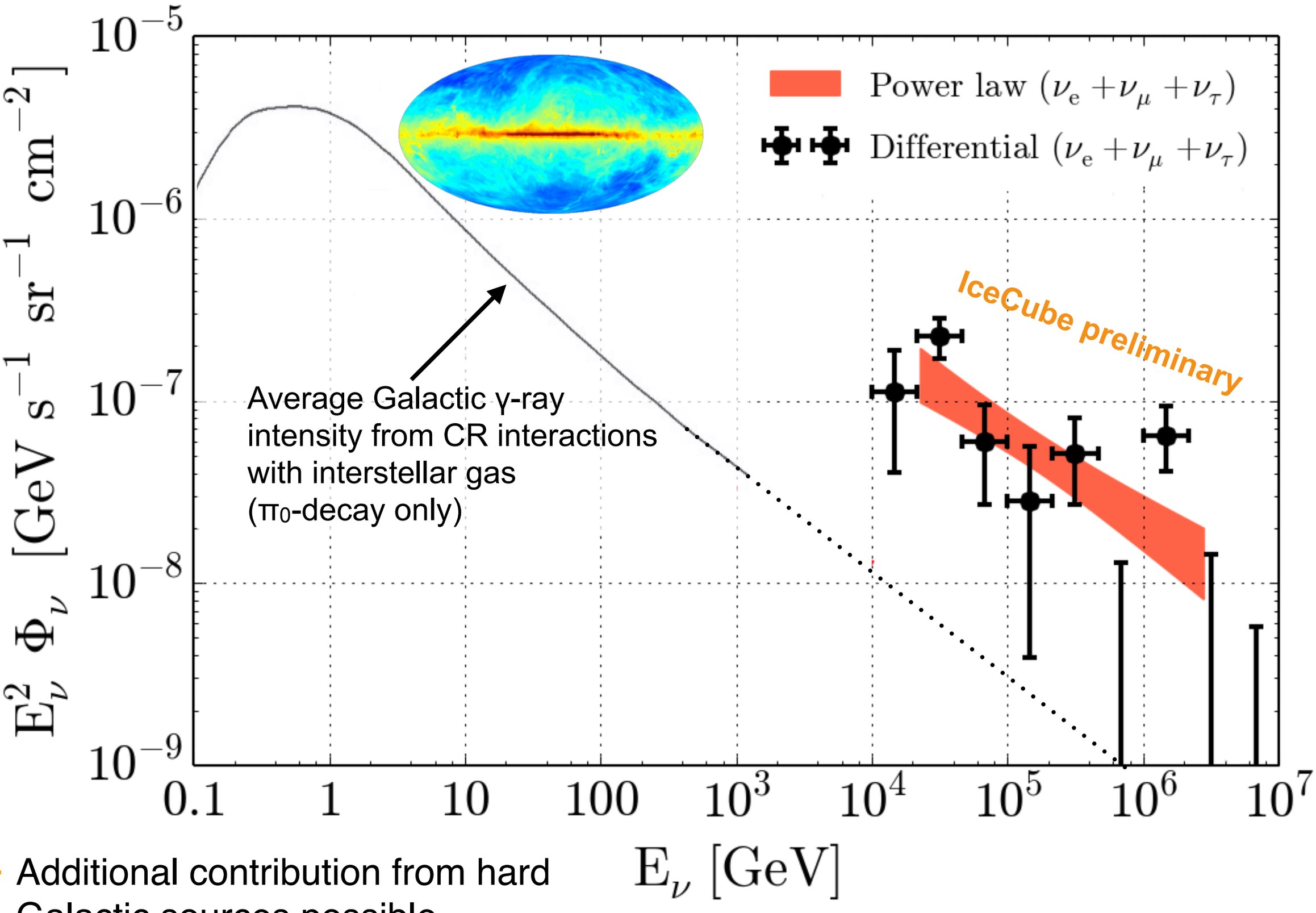




For spectral index Γ = 2.5:

$\Phi(\nu_e+\nu_\mu+\nu_\tau) = \Phi(\gamma)$

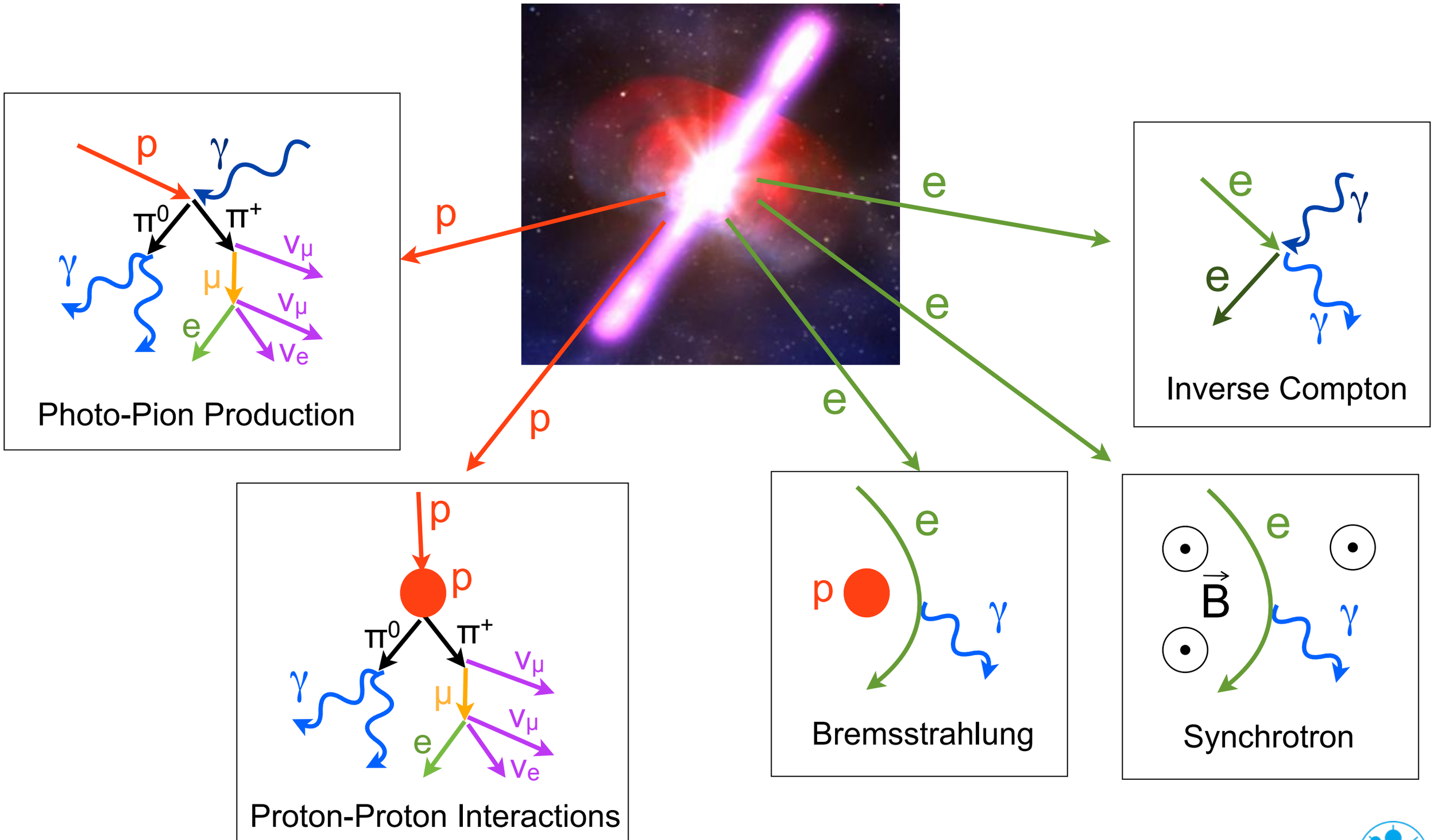
Neutrinos from CR interactions in the Galaxy ?



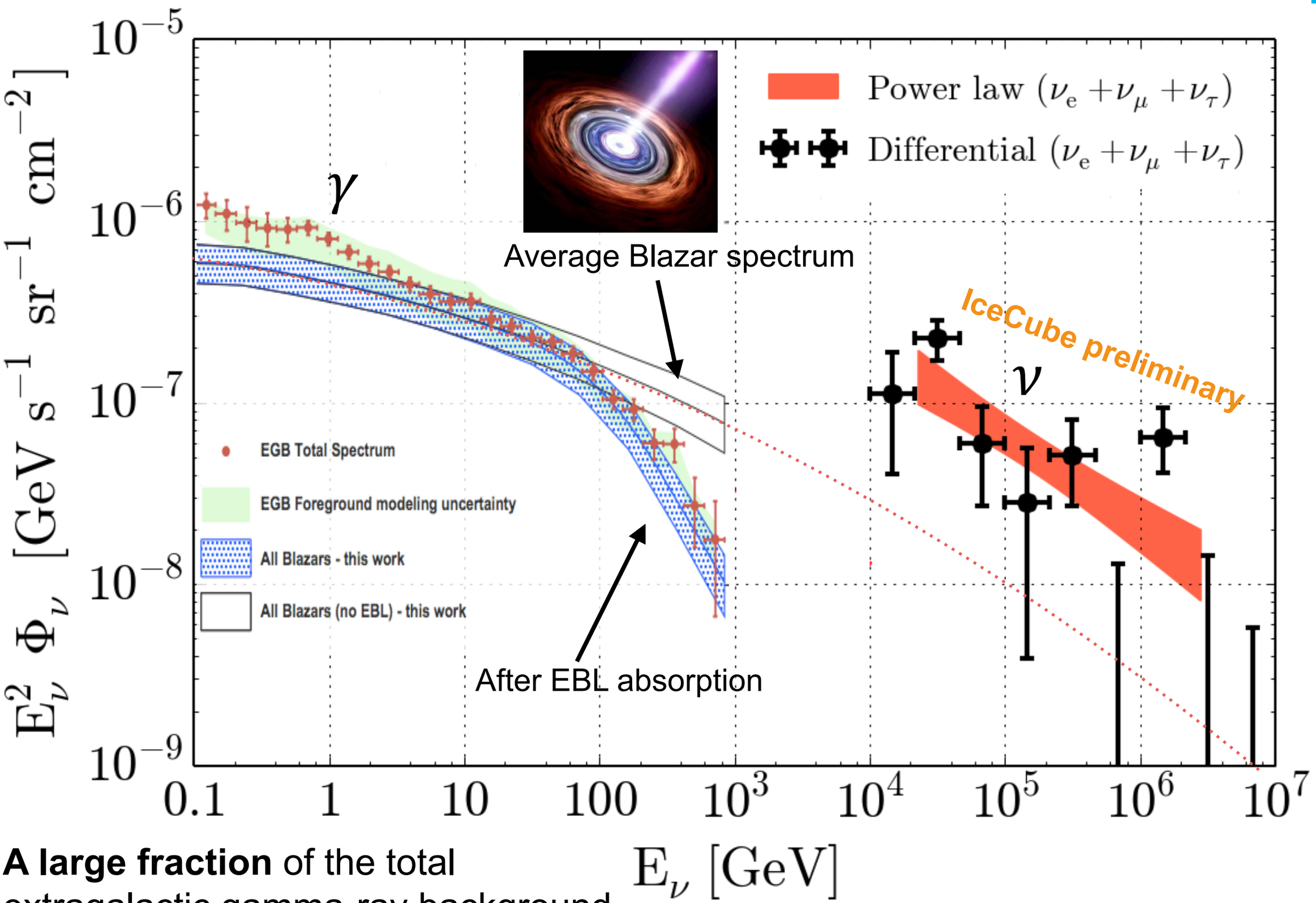
> Additional contribution from hard Galactic sources possible

The power of neutrino observations.

> Neutrinos are a diagnostic of the **acceleration sites of protons and nuclei.**



Extragalactic gamma rays and neutrinos.



A large fraction of the total extragalactic gamma-ray background is created by **Blazars**.

The Fermi LAT gamma-ray sky.

Fermi LAT, 4-year sky map, E > 1 GeV

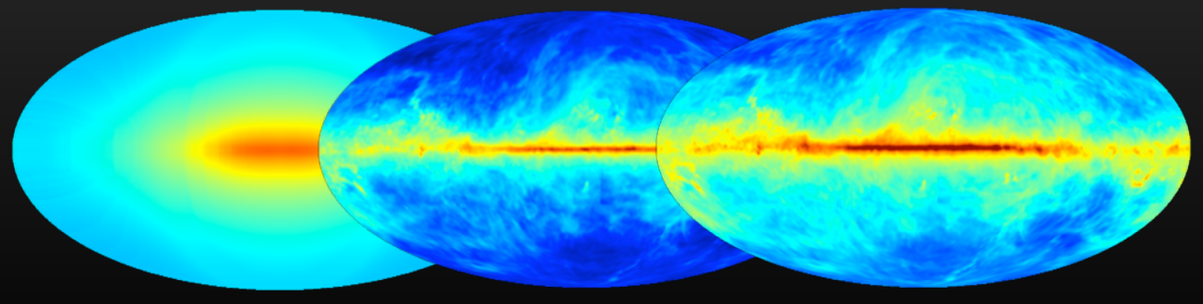
Resolved sources

Isotropic diffuse emission (IGRB)

Galactic diffuse emission
(CR interactions with the interstellar medium)

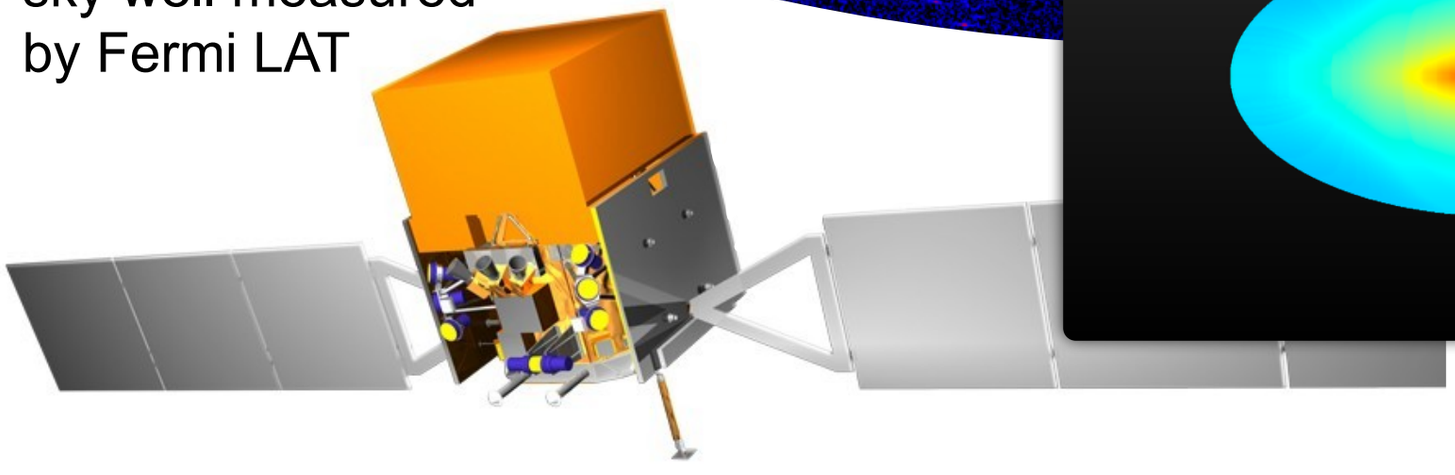
Inverse Compton

π^0-decay

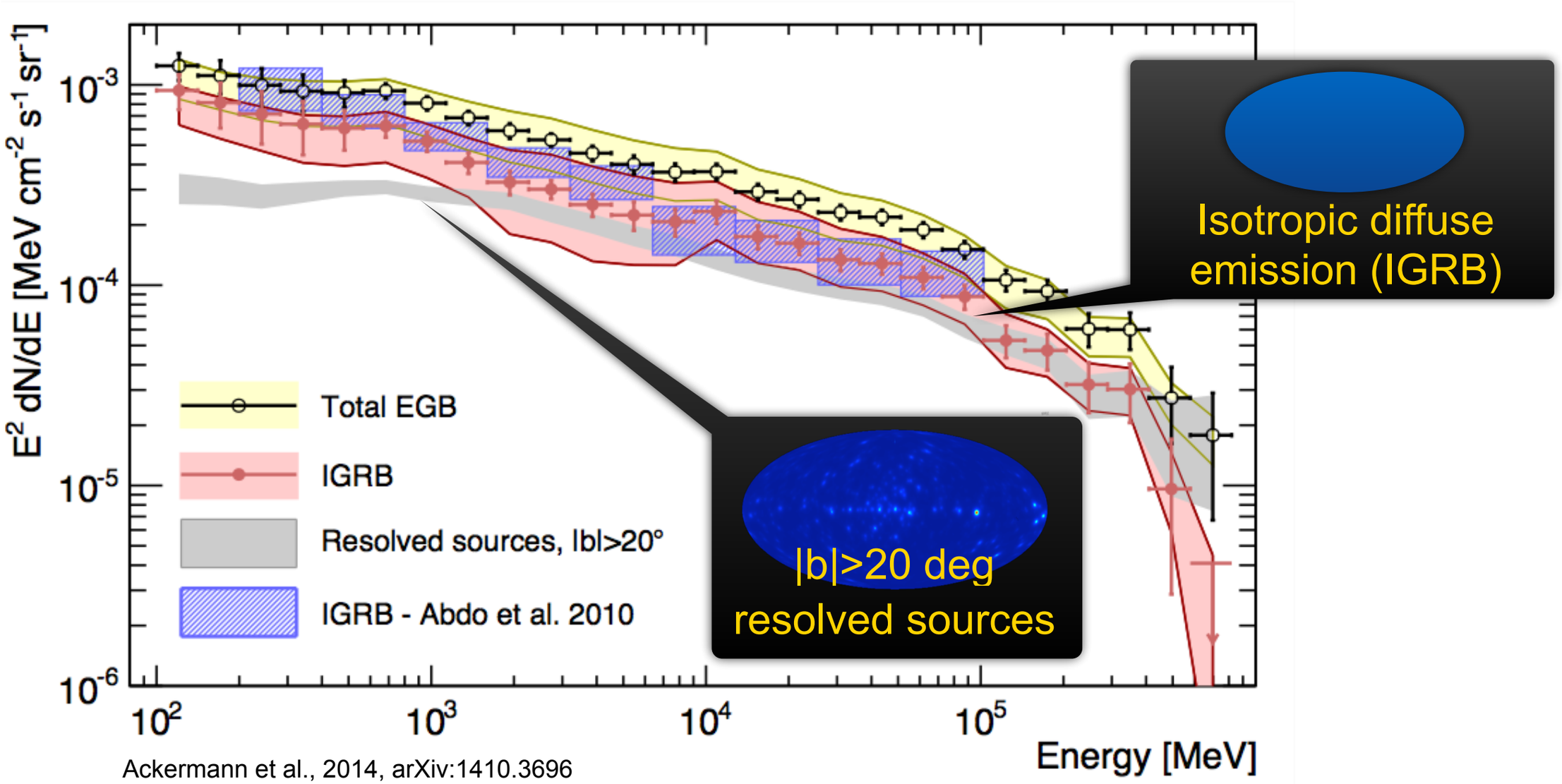


Bremsstrahlung

GeV gamma-ray sky well measured by Fermi LAT



The extragalactic GeV gamma-ray background.



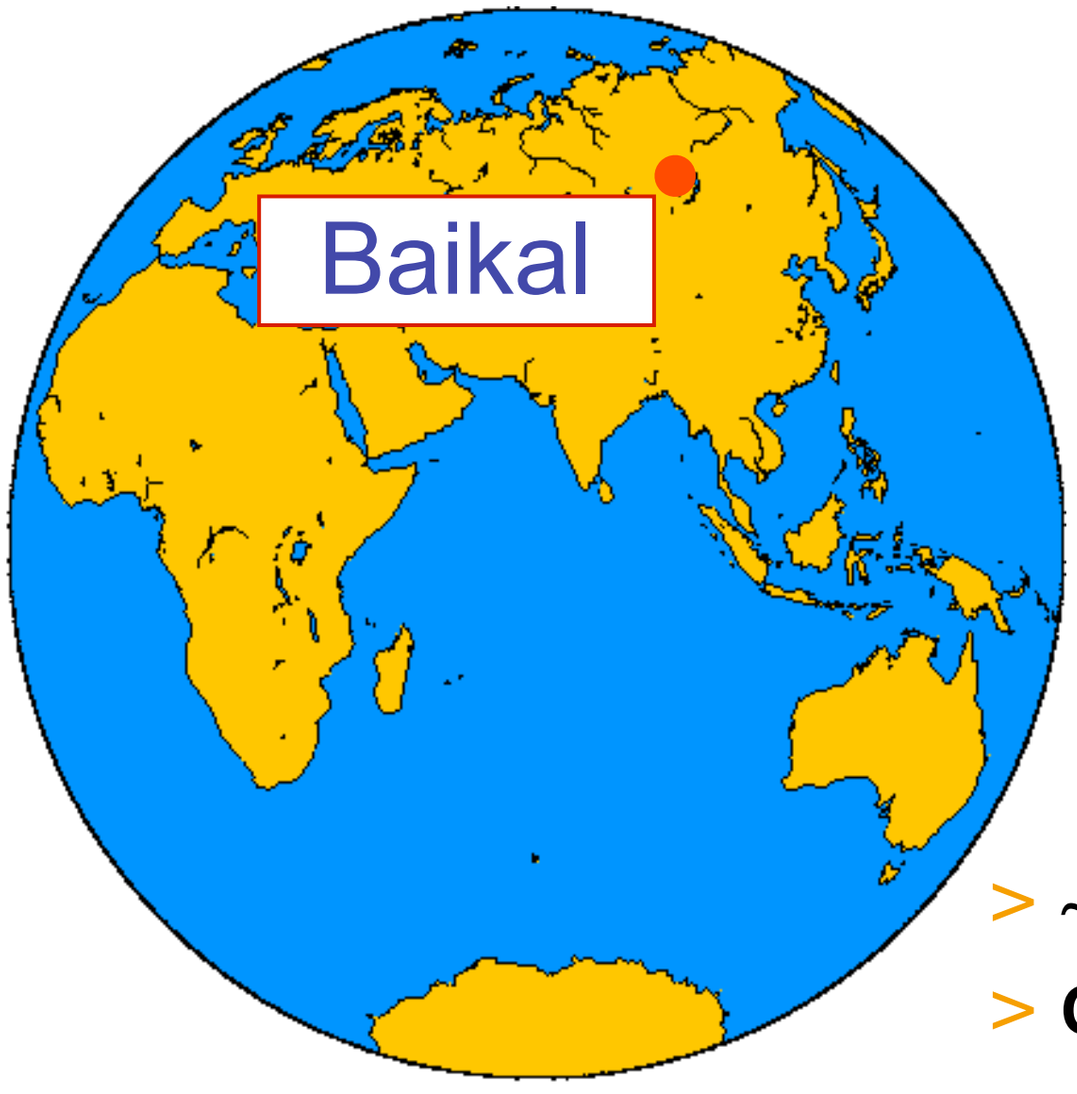
Ackermann et al., 2014, arXiv:1410.3696

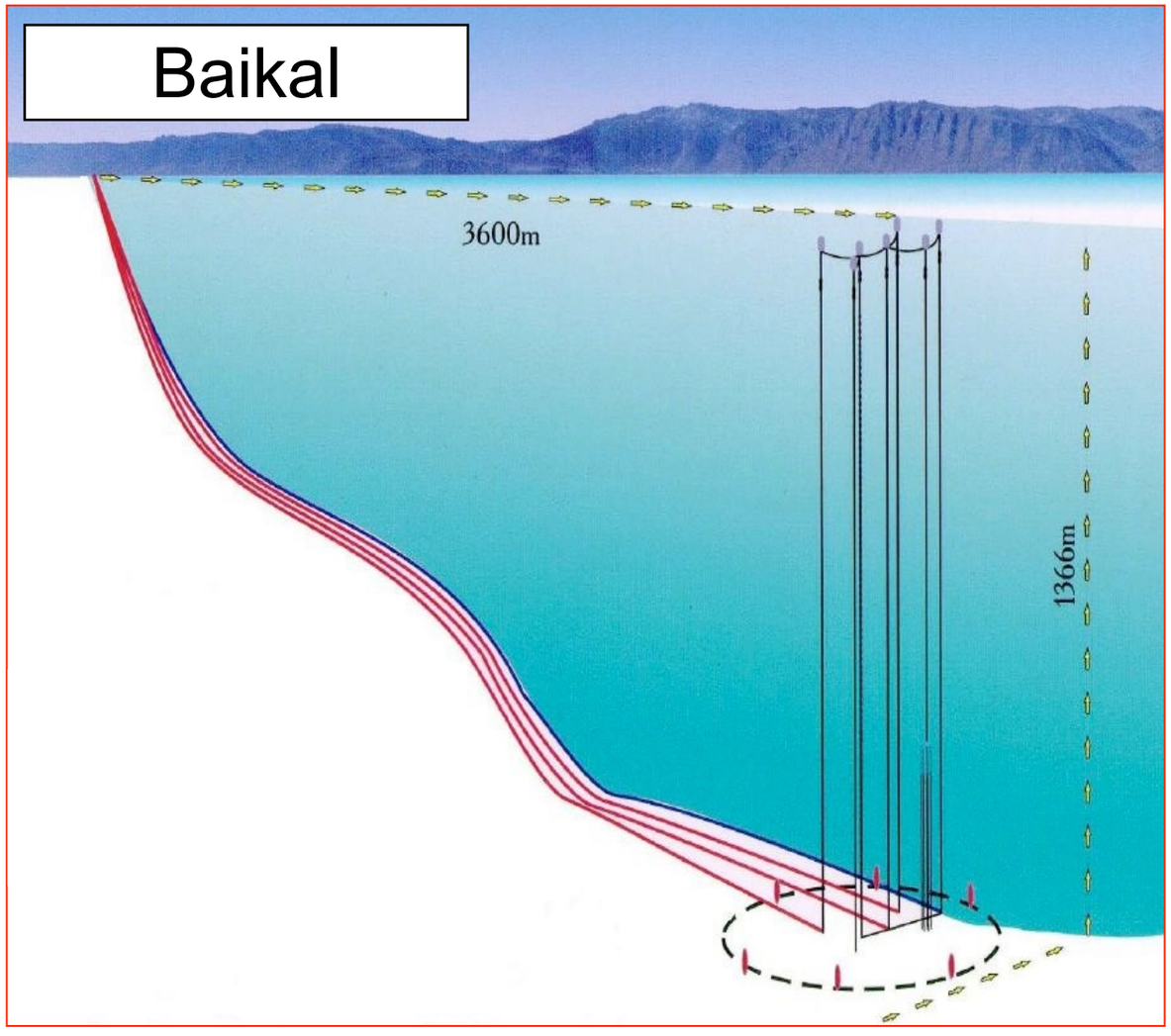
> **Resolved sources** at high galactic latitude **predominantly extragalactic**.

> **Total extragalactic gamma-ray background** (EGB) = isotropic + resolved sources.

> EGB is a measure of the **gamma-ray brightness of our universe.**

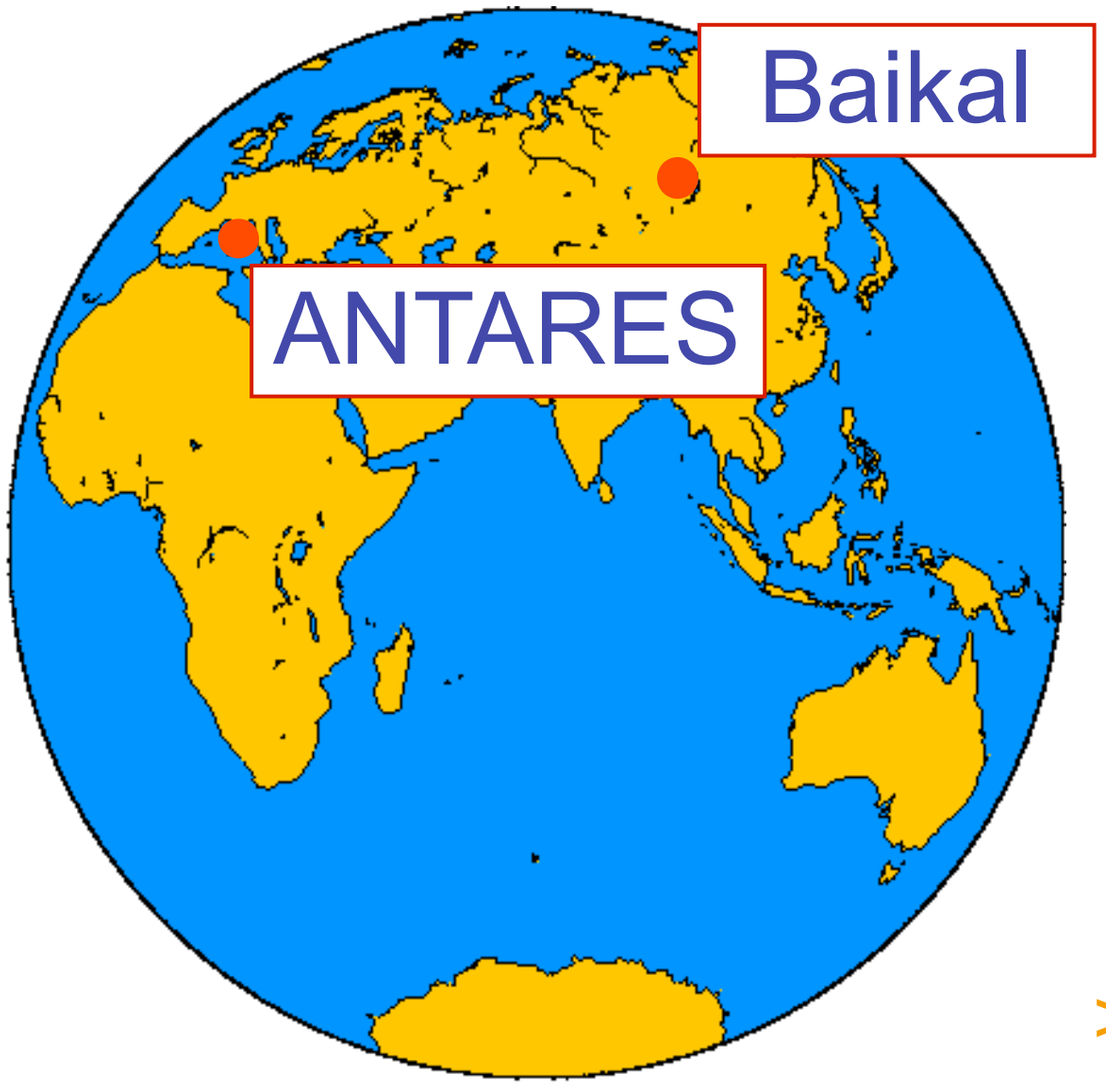
Operating neutrino telescopes: Baikal

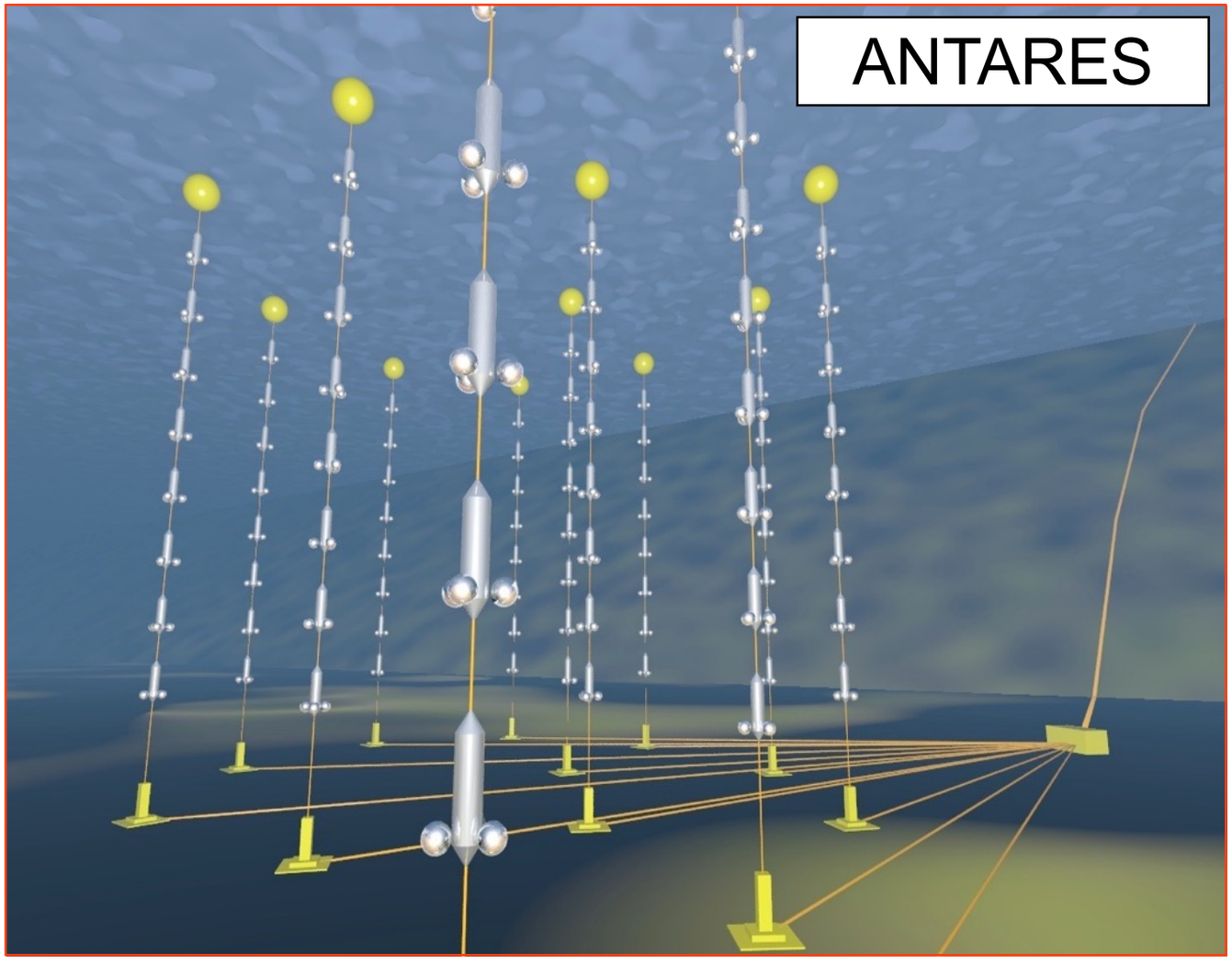




- ~ 4km off the shore of **Lake Baikal**
- **Completed** in **1998**
- 192 optical sensors on 8 strings
  (**10^{-4} km³** instrumented volume)
- Upgraded to NT200+ configuration in 2007
  (+18 sensors on 3 strings)

Operating neutrino telescopes: ANTARES



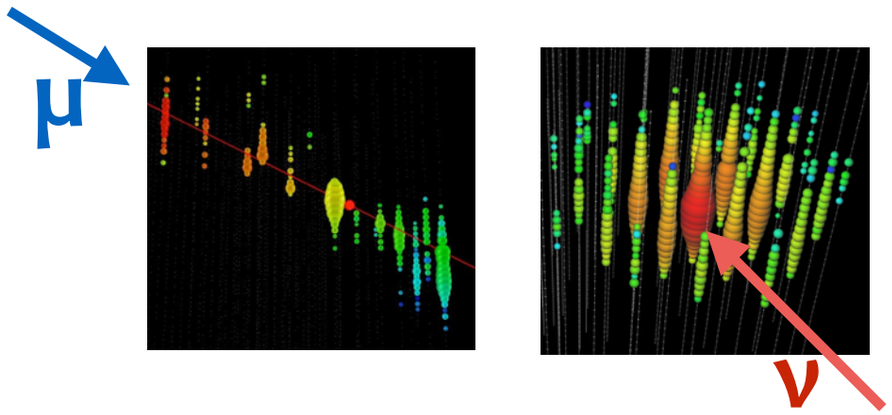


- Mediterranean sea, off **Toulon, France**
- **Operating since 2008** in final configuration
- 885 PMTs on 12 strings (~**10^{-2} km^3** instrumented volume)

The IceCube-PINGU collaboration.

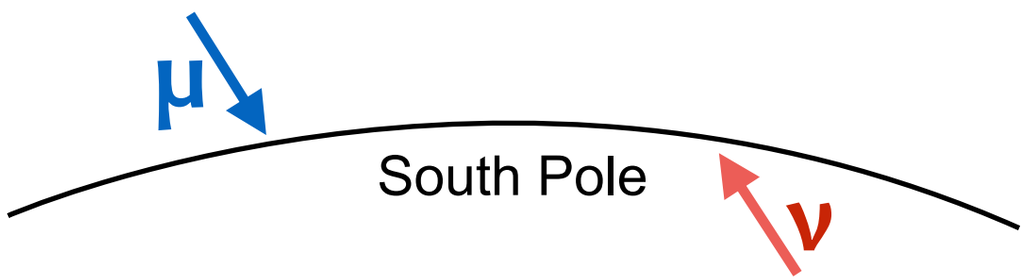
> You also need people, not only instrumentation….

Strategies to search for astrophysical neutrinos.



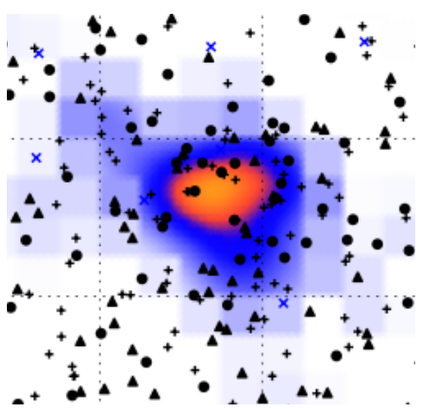
> Search for **high-energy showers** and tracks that start in the detector.

- Works on both hemispheres, good reconstruction of neutrino energy.



> Search for **high-energy tracks** from the Northern hemisphere.

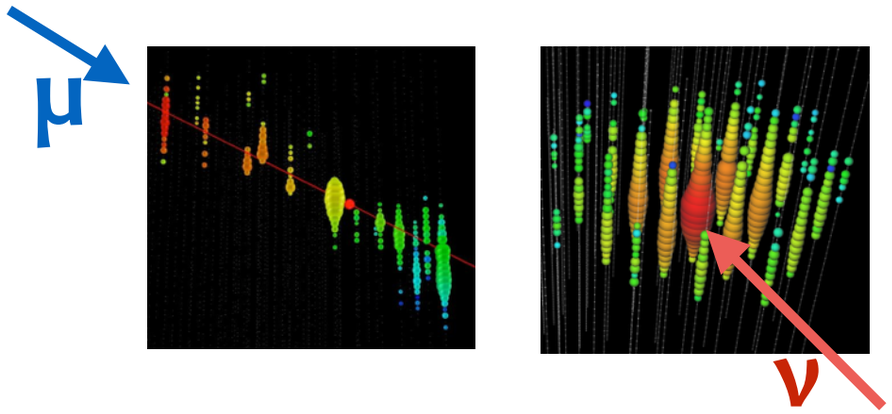
- Atmospheric muons cannot penetrate the Earth.



> Search for **individual sources.**

- Find a localized excess in the background.
- Search for transients.

Strategies to search for astrophysical neutrinos.



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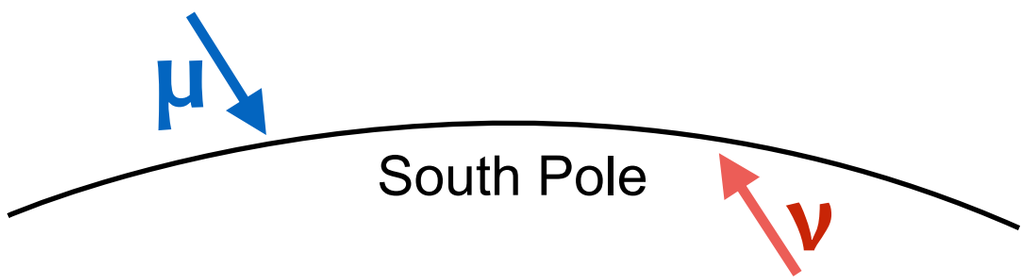

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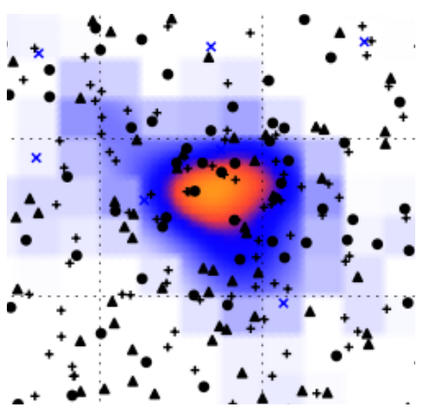

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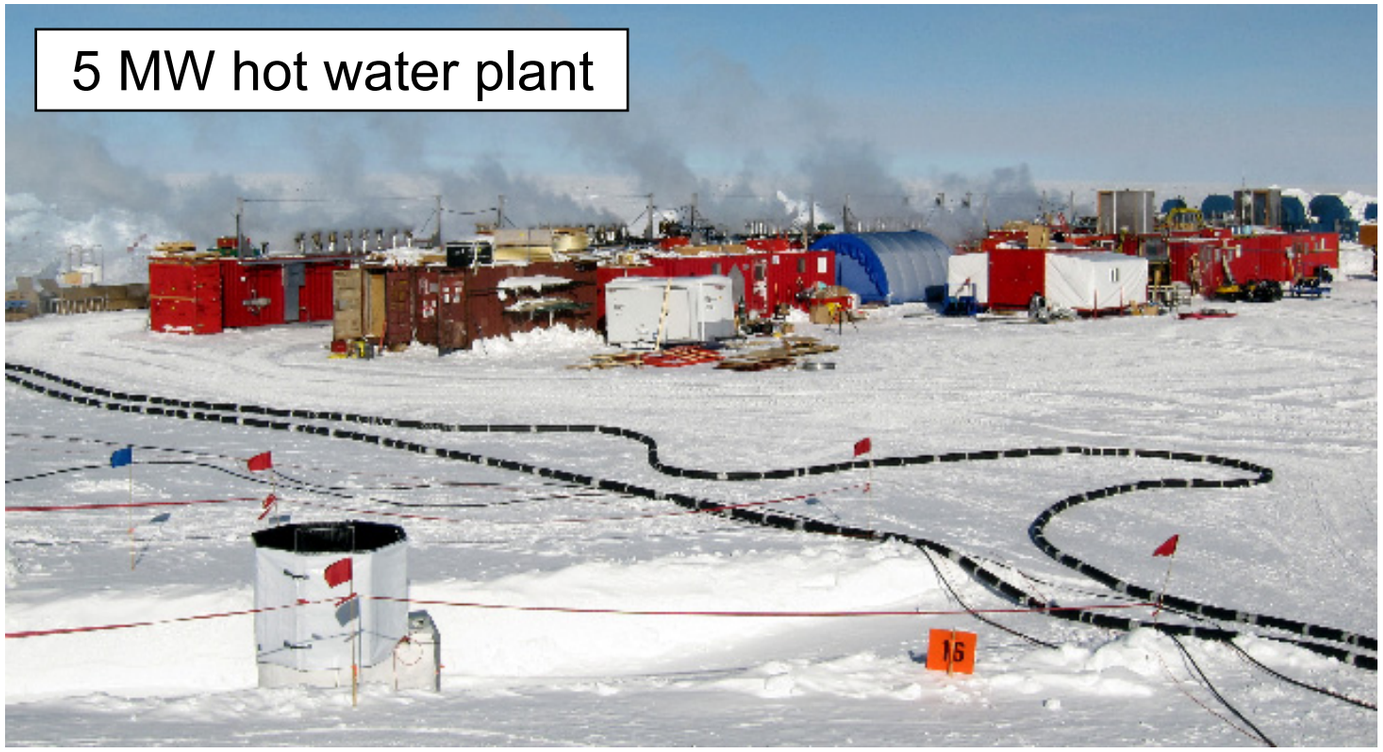
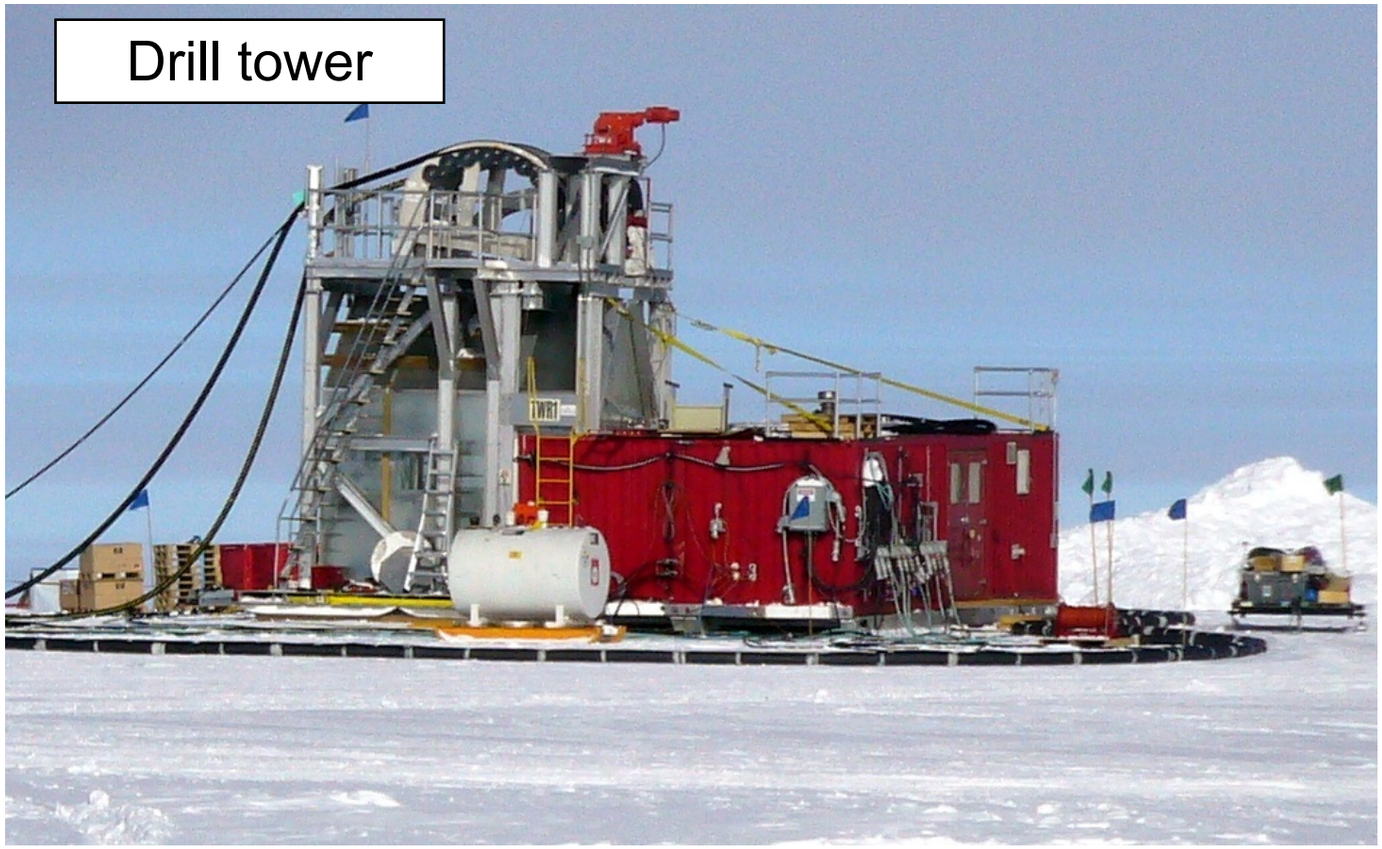
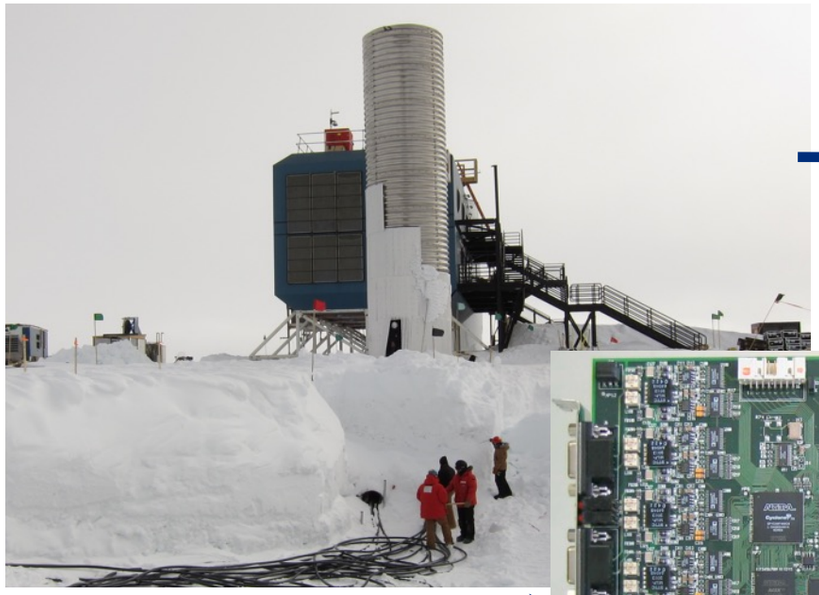
Construction of the IceCube neutrino telescope

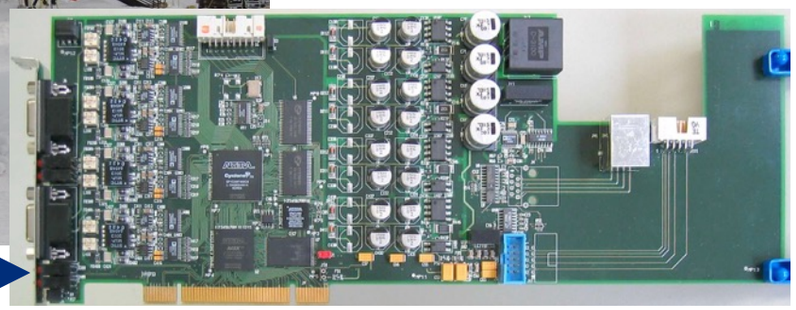




IceCube detector elements.

IceCube Laboratory
DAQ
Online filtering
Transfer
Storage



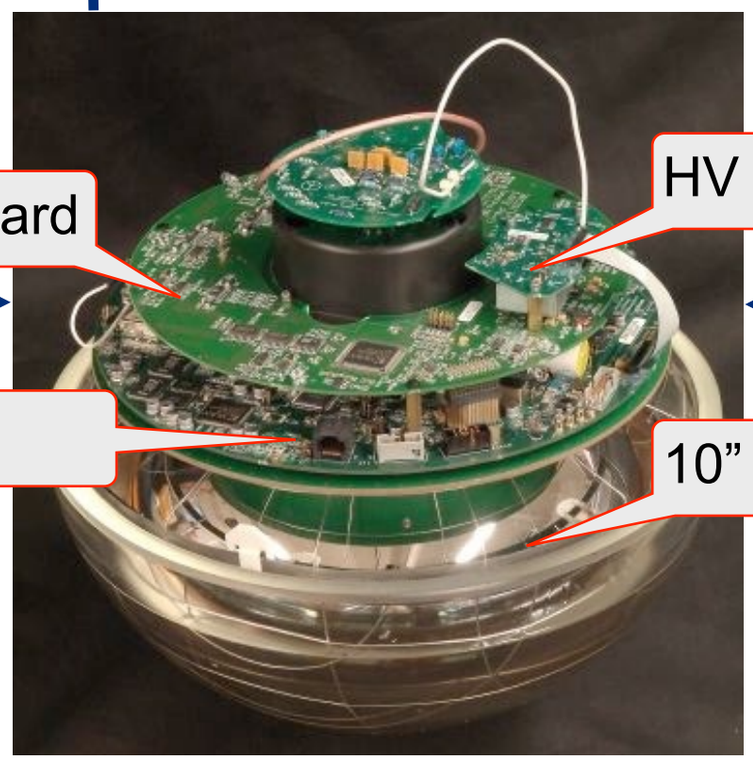


DOM receiver card

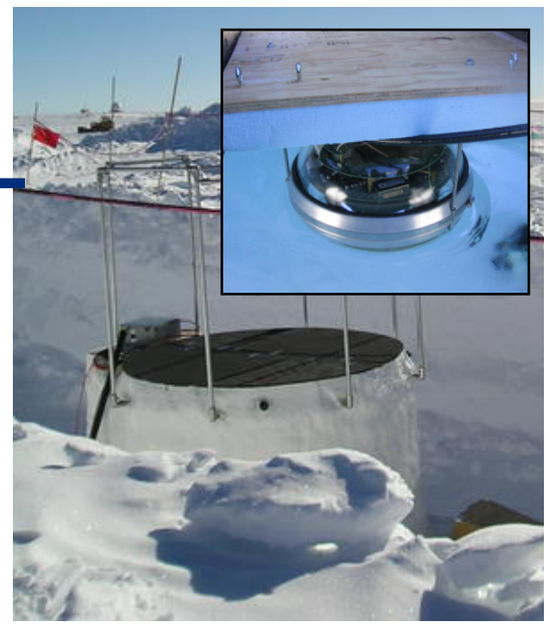
South Pole link to TDRSS satellite network

InIce Array
86 strings
60 DOMs per string

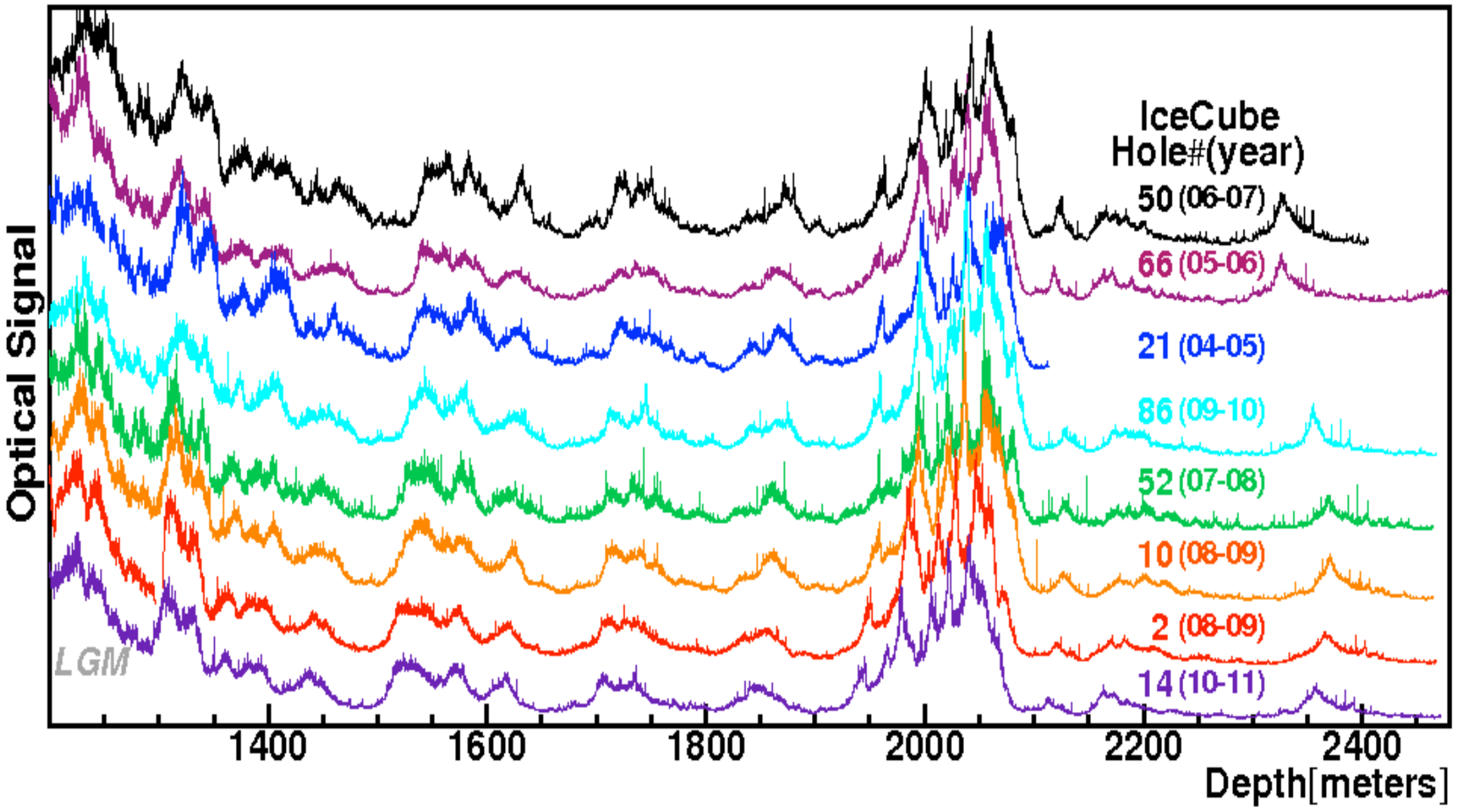
Digital optical module (DOM)



IceTop Array
81 stations
2 tanks per station
2 DOMs per tank

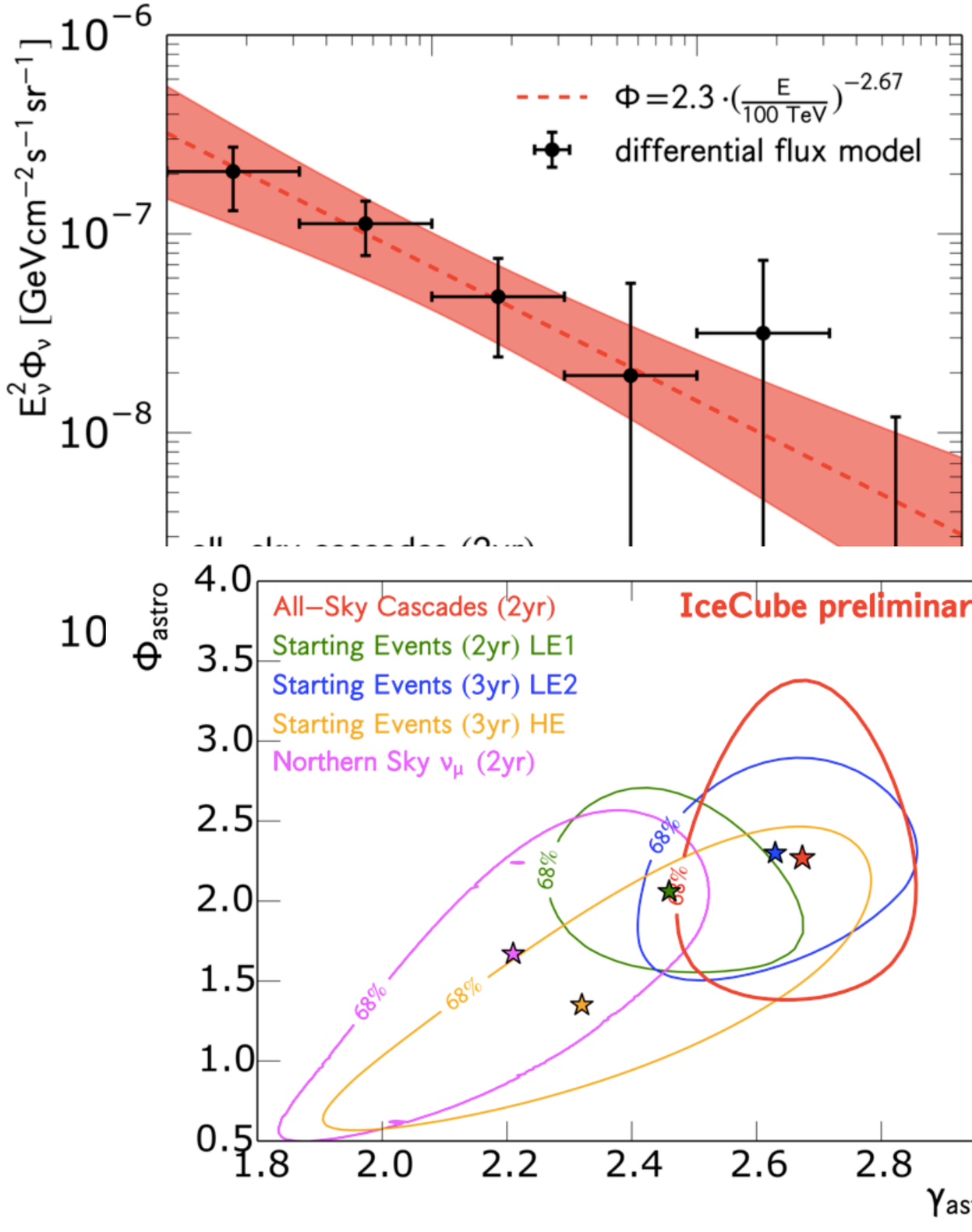


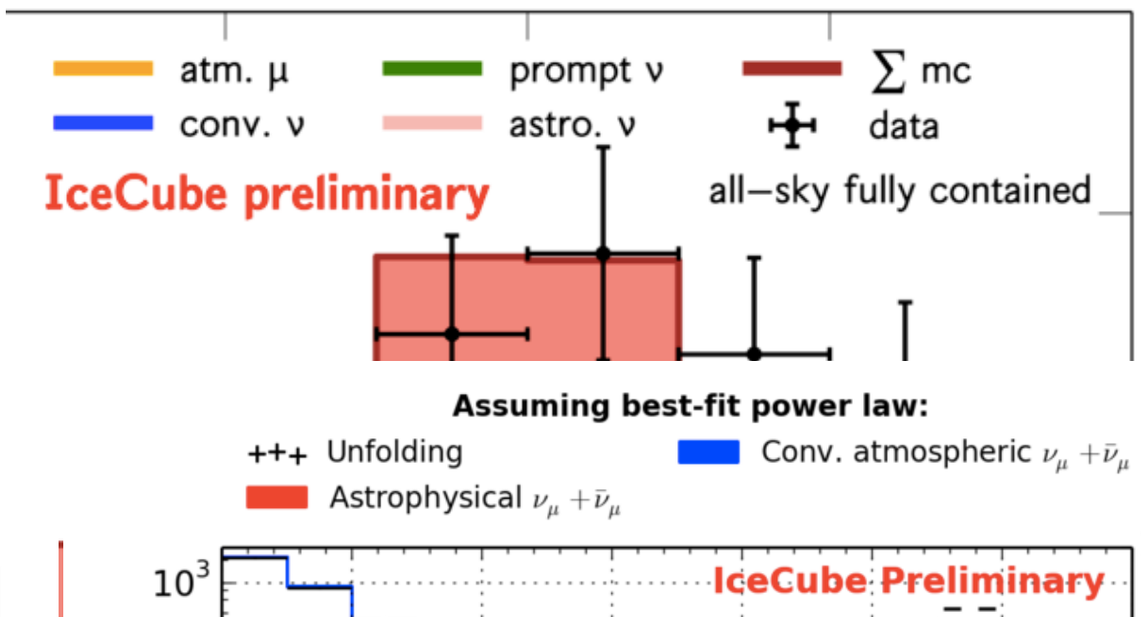
The first challenge: Optical properties of natural ice.

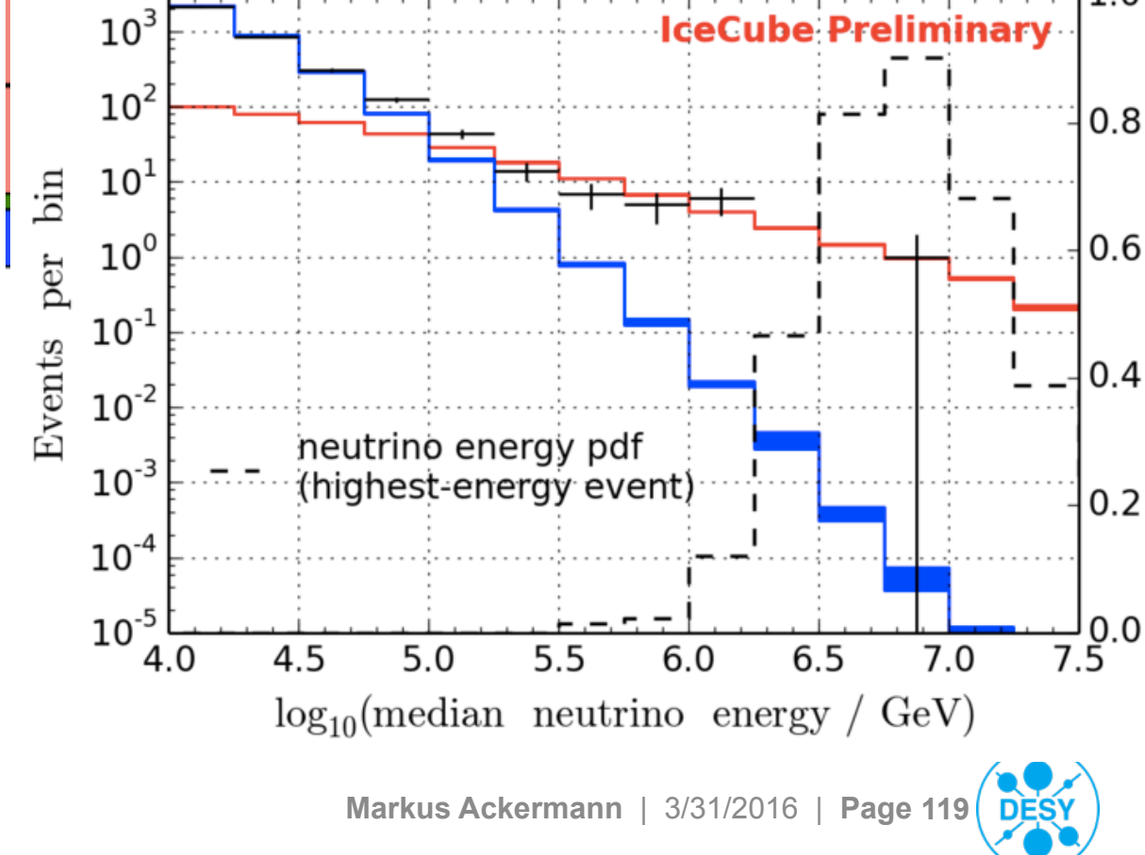


- **2500m of Antarctic ice** trace hundreds of thousands of years of Earth history.
- Light scattering and absorption properties depend **on dust / mineral deposits**.
- **Very complex** depth profile.
- Needs to be measured and **modeled properly.**

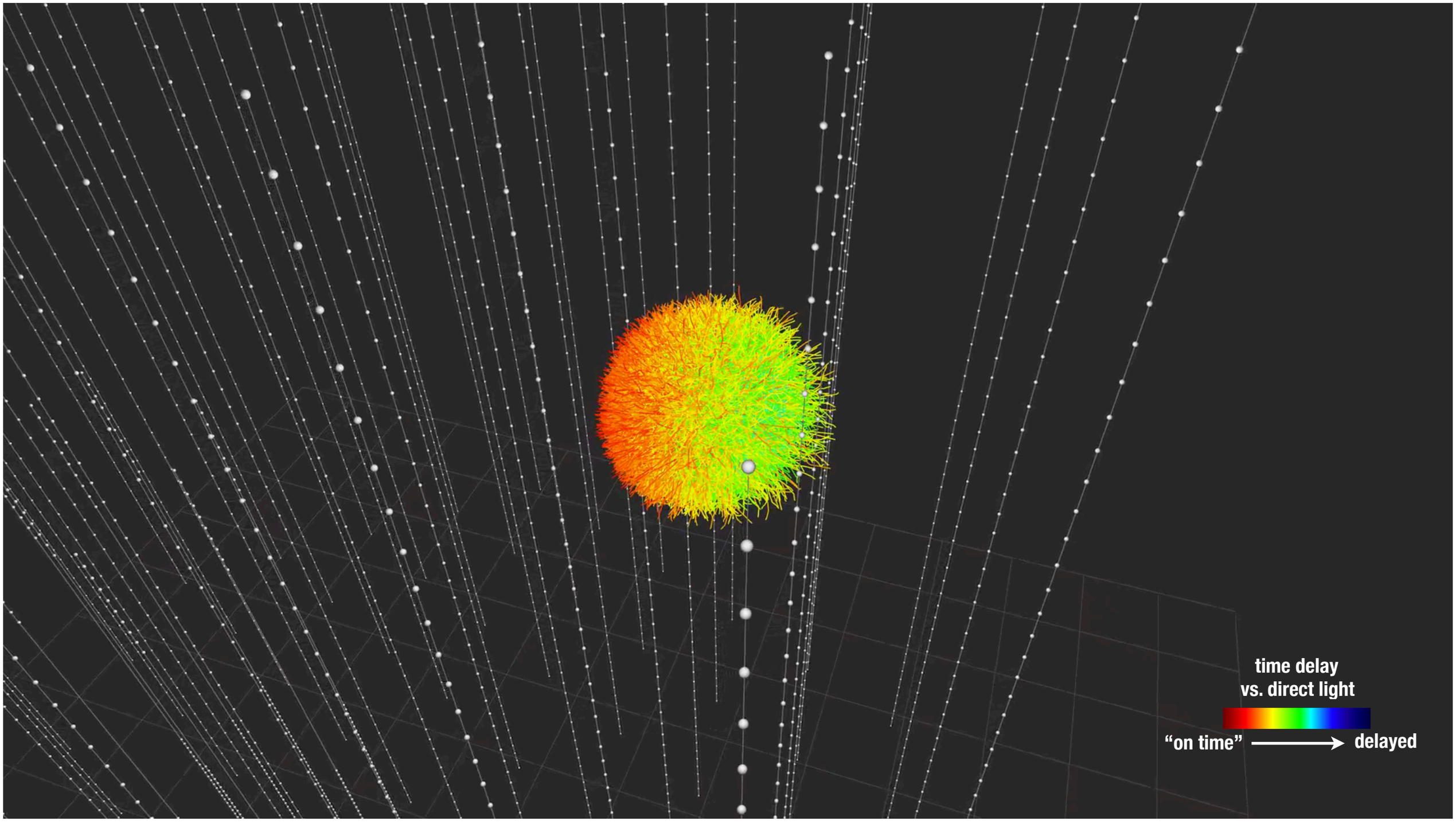
Click to add title.







Simulated light propagation from a PeV neutrino.



> Moore's law helped tremendously for modeling the ice ….

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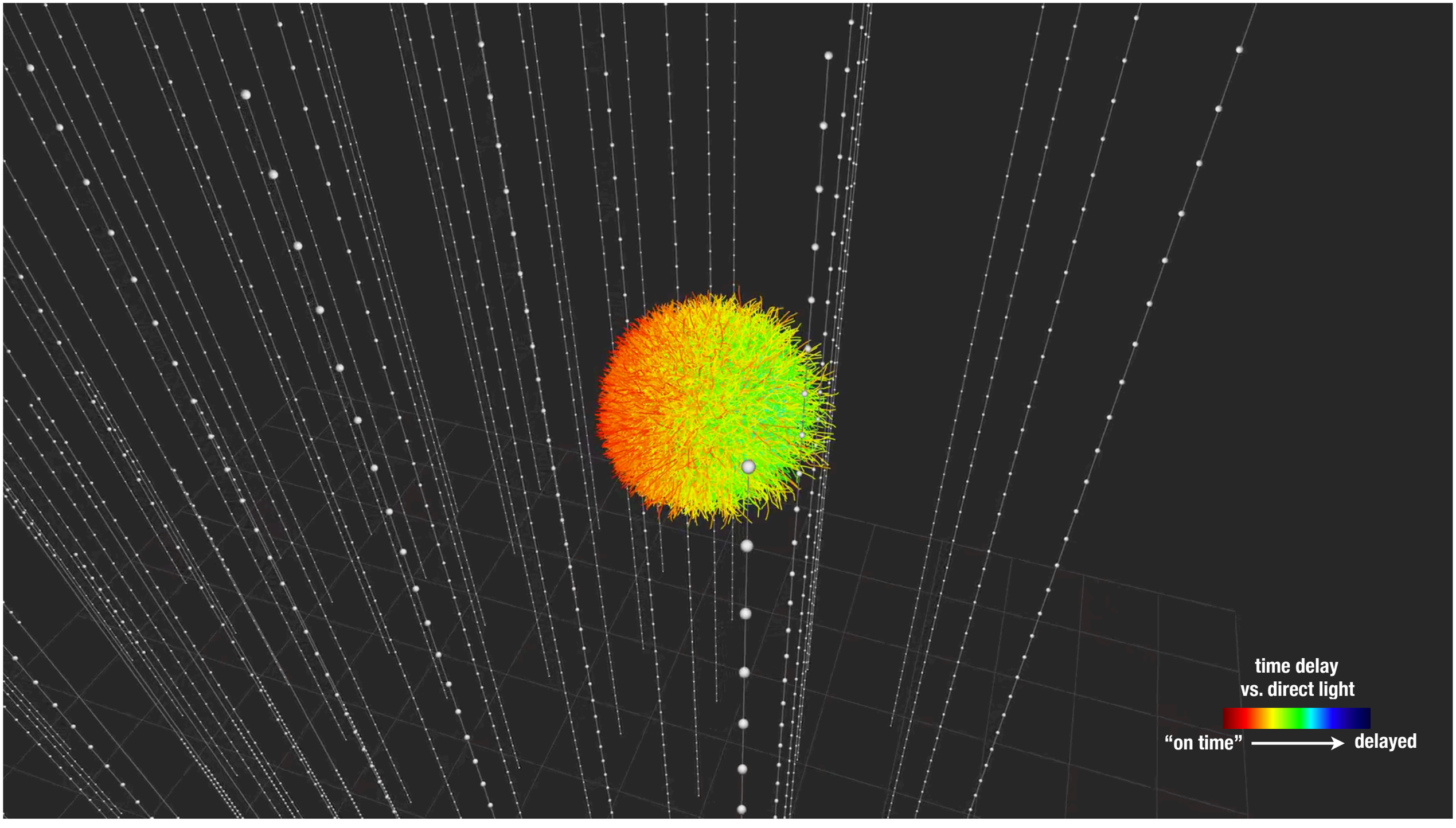

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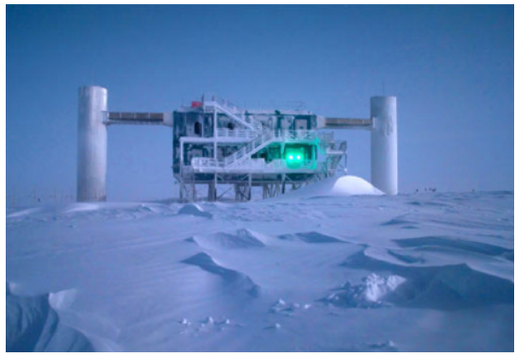
Overview.

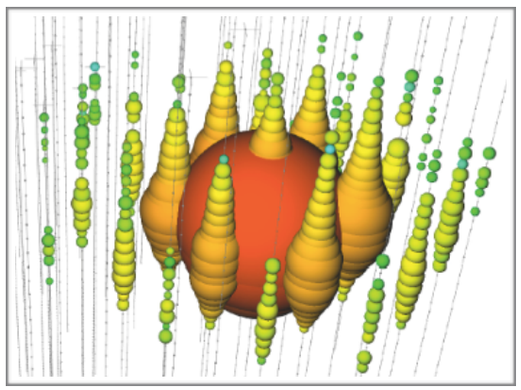
> Astrophysics with high-energy neutrinos.

- … what neutrinos can tell us no other messenger from space can.



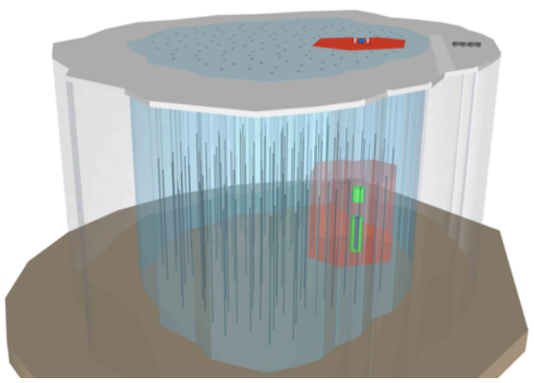
> The IceCube neutrino observatory.

- The first km^3-scale neutrino detector, buried in the Antarctic ice shield.



> Science with IceCube.

- Observations of the first TeV and PeV neutrinos from space
- … and what we learn from them.



> The future of neutrino astronomy.

- Multi-km3 detectors & precision measurements of neutrino properties.